University of Alberta

Soil respiration and carbon cycling in hybrid poplar plantations in northern Alberta, Canada

by

Daniel Denis Saurette ©

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Abstract

The use of fast-growing poplars to sequester C in biomass and soil organic matter has been proposed as a way to mitigate greenhouse gas emissions. This study examined two aspects of C cycling in hybrid poplar plantations: 1) how land-use systems affect soil respiration rates; and 2) the contributions of root (R_r) and heterotrophic (R_h) respiration to soil respiration (R_s). No differences were found in respiration rates between barley and poplar plots in the first year after land-use conversion and both were net sources of C. Net primary productivity was higher in the barley plots and was the primary factor determining the C source size. The mean contribution of R_h to R_s was 63 ± 2.6% along a chronosequence of hybrid poplar stands. No relationship existed between plantation age and R_h, R_r or R_s; possibly resulting from too few replications, restricted plantation ages and heterogeneity of soils in the region.

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1. INTRODUCTION

The global climate is changing as a consequence of human-induced perturbations to global biogeochemical cycles, notably the carbon (C) cycle (IPCC 2001; Bhatti et al. 2003), linked to a rapid increase of atmospheric carbon dioxide (CO_2) concentration (Ingram and Fernandes 2001). Estimates of total soil C losses from agricultural soils range from 20% (Mann 1986, Hansen 1993) to 50% or greater (Houghton 1999; Lal 2002). Cultivation of Canadian soils has lowered soil C levels to 65-75% of the early 1900s (25-35% C loss, Monreal and Janzen 1993; Smith et al. 2000); currently, agricultural emissions account for 10-20% of the annual increase in anthropogenic greenhouse gas (GHG) emissions (Smith et al. 2001). Reductions in residue inputs, increased decomposability of crop residues and lessening of the physical protection of soil C from soil aggregates destructed by ploughing have all been associated with soil C losses in agriculturally active soils (Post and Kwon 2000). Extensive depletion of soil C resulting from intensive agricultural production suggests that there is a large potential to store C in the aforementioned soils; hence agricultural lands are believed to be a major potential sink for CO_2 as these lands could absorb and retain vast quantities of C if trees were re-introduced (Albrecht and Kandji 2003).

Canada must reduce GHG emissions by 240 Mt CO_2 yr^{-1}, or to 6% below the 1990 level, during the 2008-12 Kyoto commitment period (Bernstein 2002). Essential components to the reduction of atmospheric GHGs are the direct reduction of emissions and removal of C from the atmosphere by sequestration into the biosphere in forms such as plant biomass and soil carbon (Ingram and Fernandes 2001) as well as through engineering means (e.g. storage of CO_2 in wells). Article 3.3[1] of the Kyoto Protocol designates afforestation as an eligible C management activity that can be used to offset net national emissions of CO_2 (Smith 1999). Tree plantations allow for sequestration of C in the form of wood biomass and the potential for accumulation of belowground C in the soil (Hansen 1993). For example, soils beneath hybrid poplar plantations in the north central United States had 24.4 Mg C ha^{-1} more soil C than adjacent soils under agricultural row crops after an average of 15 years (Hansen 1993). Furthermore, a review of 29 studies led to the conclusion that conversion of agriculture to tree plantations showed an average increase of 18% in soil C (Guo and Gifford 2002). Nonetheless, the impact of hybrid poplar plantations on C dynamics and storage on previously farmed land is virtually unknown for the boreal region on the Canadian prairies. This lack of knowledge, coupled with impending industrial requirements to report on carbon, was the incentive to develop a land-use conversion experiment in which the objective was to examine the immediate (short-term) response of an agricultural system (seeded to barley) to the establishment of a hybrid poplar plantation in terms of potential changes in CO_2 emissions (Objective 1).

Rates of soil respiration are a measure of potential soil C loss. Therefore, determining soil respiration rates and how they are affected by plantation establishment will provide a better understanding of the C sequestration potential of hybrid poplar plantations. Soil respiration (R_s) is typically separated into two components: 1) heterotrophic respiration

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[1] Article 3.3. The net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period, shall be used to meet the commitments under this Article of each Party included in Annex I. (UNFCCC 1997)

(R_h), which is the portion of the CO_2 efflux derived from soil microorganisms feeding primarily on detritus (Lavigne et al. 2003), and 2) root respiration (R_r), which is the respiration derived from roots, including associated mycorrhizal fungi and micro-organisms in the rhizosphere that feed directly on root exudates (Bhupinderpal-Singh et al. 2003). In terms of global warming and understanding the implications of environmental change on C cycling and sequestration, comprehensive knowledge of the contributions of both components to soil respiration must be acquired (Hanson et al. 2000) as the two components of soil respiration will respond differently to changes in environmental conditions associated with climate change. A wide range of percentage contributions of root respiration to total soil respiration have been reported in the literature. The largest range was 10-90% reported by Hanson et al. (2000) in a review of the literature, with a mean value of 45.8%. Numerous studies conducted in a variety of ecosystems around the world have reported values similar to the mean value above (see Ohashi et al. 2000; Widen and Majdi 2001; Schuur and Trumbore 2006). The current study assessed the contribution of soil respiration components across four different stand ages; to my knowledge, this is the only study that assessed the contribution of R_r and R_h to R_s in a chronosequence of plantation stands. In a recent review of the literature, Subke et al. (2006) found only three studies that investigated age-related contributions of heterotrophic and root respiration to soil respiration. Thus far, relatively little knowledge is available in the literature about the age effect on contributions of R_r and R_h to soil respiration (3 studies), no studies have reported on these components in tree plantations and the importance of understanding the contributions to soil respiration to elucidate responses to climate change remains unknown. In light of this gap in knowledge, I designed a root exclusion experiment to determine the contribution of root respiration to total soil respiration in a chronosequence of hybrid poplar plantations (Objective 2).

Four hypotheses were tested in this thesis research. Hypotheses 1 and 2 relate to Objective 1, the land-use conversion experiment, and Hypotheses 3 and 4 relate to Objective 2, the root exclusion experiment.

Hypotheses:

1) Soil respiration rates are higher in the barley as compared to newly established hybrid poplar plantation due to lower fresh C inputs in the hybrid poplar plantation (Chapter 3).
2) Dissolved soil organic C (DOC) in the surface horizons is lower in the hybrid poplar plantations, again due to lower fresh C inputs (Chapter 3).
3) Root respiration will increase with stand age as root biomass increases (Chapter 4).
4) Root respiration will represent a higher proportion of total soil respiration as plantation age increases (Chapter 4).

Two field experiments were designed to test the hypotheses listed above. The first experiment was a land-use conversion trial comparing respiration rates and soil characteristics between barley plots and hybrid poplar plots. The second experiment was intended to test hypotheses 3 and 4. This experiment studied the contribution of root and heterotrophic respirations to soil respiration.

This thesis is separated into five chapters: the current chapter, Chapter 1, serves as an introduction to the entire thesis. Chapter 2 is a literature review which synthesizes the most pertinent information regarding the carbon cycle, soil respiration and its components, influences of abiotic factors on soil respiration, techniques used for soil respiration measurement, and the effect of land-use conversion on soil carbon pools. The third chapter reports the effects on soil respiration of converting agricultural land-use to hybrid poplar plantation. Chapter 4 discusses the relative contribution of R_r and R_h to total soil respiration in a chronosequence of hybrid poplar plantations. The final chapter is designed to provide a synthesis of the two field experiments and to provide some direction for future research in this field.

The results obtained from this thesis will fill knowledge gaps that exist in the field of soil C cycling, with emphasis on soil respiration. The knowledge gained will provide resource managers and government officials valuable information which can be used in the development of new initiatives aimed at reducing net GHG emissions by sequestering C in soils. Little information is currently available regarding the potential for C sequestration in hybrid poplar plantations established in former agriculturally active soils in Canada; hence this study will be invaluable as it makes the first contribution regarding afforestation with hybrid poplars which will likely play an important role in Canada's efforts to meet its commitments under the Kyoto Protocol.

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2. LITERATURE REVIEW

The Kyoto Protocol, ratified by Canada, sets quantitative limits of greenhouse gas (GHG) emissions (West and Marland 2002). In the Kyoto protocol, afforestation is an eligible activity that allows nations to mitigate GHG emissions through sequestration of carbon dioxide (CO_2) into the biosphere; however, the impact of hybrid poplars on carbon (C) dynamics and storage on previously farmed land is largely unknown for the boreal region of the Canadian prairies. The objective of this literature review is to synthesize results from previous research and relate them to the current study. With the information collected in this review, several well-constrained hypotheses were developed focusing on C cycling, specifically soil CO_2 efflux, in hybrid poplar plantations. This literature review summarizes previous work conducted on various central aspects of C sequestration research. In this chapter, I will review the C cycle, summarize soil respiration and its components, describe the effect of abiotic factors on soil respiration, compare various methods of measuring soil respiration, report on the effect of agricultural production on soil C stores, discuss the effects land-use conversion from agricultural row crop to tree plantations on soil C and put hybrid poplar research, including public and private sector initiatives in Canada, into context with the Kyoto Protocol.

2.1. The Carbon Cycle

The biogeochemical C cycle describes the circulation of C between four main pools of actively cycled carbon (Fig. 2.1): 1) atmospheric CO_2, 2) biota (mostly vegetation), 3) soil C and 4) oceans (Janzen 2004). Carbon enters the biota from the atmospheric pool as

CO_2 via photosynthesis, a flux reported to be approximately 120 Gt C yr^{-1} and referred to as gross primary productivity (GPP, Schlesinger and Andrews 2000; Janzen 2004). About half of GPP is returned to the atmosphere via plant respiration (40-60 Gt C yr^{-1}, Janzen 2004). The largest flux of C to the atmosphere is through soil respiration, a value reported to range from 50 to 76.5 Gt C yr^{-1} (Bowden et al. 1998; Raich and Potter 1995; Schlesinger and Andrews 2000; Conant et al. 2004). The release of C from the ocean to the atmosphere is almost identical to the absorption of C by the ocean and is reported to be about 90 Gt C yr^{-1} (Schlesinger and Andrews 2000). The oceanic C pool is reported to range from 38,000-39,000 Gt C, the atmospheric pool is estimated between 720-760 Gt C, the biota C pool ranges from 500-600 Gt C and the soil C pool is currently reported to be 1500-2000 Gt C (Schlesinger and Andrews 2000; Janzen 2004; Powlson 2005). The four main pools of C were believed to be in dynamic equilibrium until the recent unprecedented alterations imposed by man (Rustad et al. 2000). During the 1990s, fossil fuel burning and land conversion accounted for annual emissions of 5.4-6.3 Gt C and 2 Gt C, respectively, which resulted in an atmospheric C pool increase of 3.2 Gt C yr^{-1} (Sundquist 1993; Janzen 2004).

2.2. Soil Respiration and Partitioning of Heterotrophic and Root Derived Contributions

Soil respiration is the sum of heterotrophic and autotrophic respiration (Hanson et al. 2000). Autotrophic respiration, or root respiration (R_r), is defined as "respiration by roots, their associated mycorrhizal fungi and other micro-organisms in the rhizosphere directly dependent on labile C compounds leaked from roots" (Bhupinderpal-Singh et al. 2003).

Heterotrophic respiration (R_h) is the portion of the CO_2 efflux from soils derived from soil microorganisms which feed primarily on detritus (Lavigne et al. 2003). Scientists have recognized the important role of roots in soil C fluxes for many years; however quantifying the contribution has proven very difficult (Ross et al. 2001). Of main importance in terms of global warming are the different temperature sensitivities of both the heterotrophic and autotrophic components of soil respiration (Boone et al. 1998), particularly to understand the implications of future changes to climate and vegetation and their effect on net ecosystem exchange of C (Schuur and Trumbore 2006).

Numerous methods have been utilized in both laboratory and field experiments to isolate the different components of soil respiration with varying levels of success. In a thorough review of pertinent literature, Hanson et al. (2000) identified three main categories of methodological approaches: 1) component integration methods, 2) root exclusion methods, and 3) isotopic methods. The component integration method separates the different components contributing to soil respiration and evaluates them individually. In essence, this method separates roots, sieved soil and litter and measures the efflux from each. The values are summed and compared to total soil respiration measurements taken *in situ* at the time of sample collection (Hanson et al. 2000). A common deviation of this method is to measure respiration *in situ*, the root and litter contributions in the laboratory, and calculate the sieved soil fraction by subtraction (Hanson et al. 2000). The component integration method has been praised for being relatively inexpensive; however it has been criticized for being laborious, creating high CO_2 flushes after soil disturbance and altering the CO_2 concentration surrounding the roots during measurement (Kuzyakov

2006), which is usually much higher in soil than in ambient air. Maier and Kress (2000) reported a large difference between ambient and soil atmosphere concentrations of CO_2, 400 and 1000 μmol mol^{-1}, respectively, which lead to overestimates of root respiration because root respiration rates decrease as the CO_2 concentration around the root increases. A slight deviation from the component integration method is to measure respiration by excised roots. In this method, roots are removed from soil and respiration rates are measured separately. This method again has been criticized because of strong CO_2 fluxes after the disturbance (Kuzyakov 2006). A new method not reviewed by Hanson et al. (2000) uses tree girdling in large plots. The girdling method involves the complete removal of the tree bark in a ring around the stem to the depth of current xylem (Bhupinderpal-Singh et al. 2003), which instantaneously terminates the supply of photosynthates to the tree roots (Hogberg et al. 2001). The established plots include a sufficient amount of girdled trees to prevent cross-over of live roots from surrounding live trees. This method has the advantage of eliminating respiration by roots without creating a major soil disturbance. Furthermore, this enables water movement through the xylem to the canopy, hence having no short-term impacts on soil physical characteristics such as temperature and moisture (Hogberg et al. 2001).

The second approach is the root exclusion method. This approach encompasses any method that estimates R_r by measuring soil respiration in soils with and without roots (Hanson et al. 2000). There are three techniques commonly used: root removal, trenching and gap analysis. Root removal involves disturbing the soil to remove a core, retrieving the roots from the core, and replacing it into position with a barrier to prevent root ingrowth (Hanson et al. 2000). Trenching involves digging a trench or cutting the soil along a plot boundary to the depth of root growth. This severs the roots, and a barrier is installed to block root ingrowth (Lavigne et al. 2003). The trench is backfilled with original material after the barrier has been placed. The root exclusion method by trenching has two major deficiencies: 1) it results in a large-scale soil disturbance from digging the trenches, and 2) there is great difficulty in calculating the contribution of rapid decomposition of fine and coarse roots that have been severed from the surrounding trees to soil respiration in the trenched plot. Despite these criticisms, Bond-Lamberty et al. (2004b) reported in their review that root exclusion studies did not differ significantly from studies based on other types of measurements. Gap analysis simply involves the removal of above-ground vegetation from large areas and soil respiration is subsequently compared between the gap and the adjacent intact forest (Hanson et al. 2000; Ohashi et al. 2000).

The third method for separation of soil respiration components is the isotopic method. There are numerous approaches (pulse labeling, repeated pulse labeling, continuous labeling, etc.) based on the same principle. They all involve the addition of an isotopic tracer, either ^{14}C or ^{13}C labeled CO_2, to quantify the distribution of labeled C within the plant and the amount respired by above- and belowground plant parts (Hanson et al. 2000).

A review by Bond-Lamberty et al. (2004b) of 54 forest sites that were studied using a variety of the aforementioned techniques reported that in all cases, there was a positive relationship between both R_r and R_h and soil respiration. Furthermore the authors concluded that there was no effect of biome type, measurement method, precipitation, latitude or soil drainage on these observed relationships. Interestingly, Bond-Lamberty et al. (2004b) found that isotope studies were consistently reporting lower values of the contribution of R_r to R_s; nevertheless, autotrophic respiration was predicted to be 30-50% of soil respiration. This range corresponds well with an average contribution of R_r of 48.6% from a review of 37 studies in forested regions by Hanson et al. (2000). In a tree girdling experiment of a 45-55 year-old Scots pine (*Pinus sylvestris* L.) stand in Sweden, Hogberg et al. (2001) concluded that R_r was 52-56% of soil respiration; although the authors believe this may be a conservative estimate as they did not consider the effect of possible root decay and decomposition by heterotrophs in the soil surrounding the girdled trees. In a follow-up study completed in the second year after girdling on the previous site, Bhupinderpal-Singh et al. (2003) reported that R_r represented 65% of soil respiration. In a 26 year-old *Pinus radiata* D. Don site in New Zealand, the contribution of roots to respiration ranged from 55-60% (Ross et al. 2001). The authors also concluded that the decrease in soil respiration observed in the trenched plots was due to a reduction of extractable C and microbial C, which in turn hindered soil microorganism respiratory processes. A greenhouse study using a variation of the excised root technique reported a range of contribution of roots to soil respiration of 43-66% in young (2-45 weeks old) radiata pine (Chen et al. 2006). Widen and Majdi (2001) reported an autotrophic component responsible for 12-62% of soil respiration in a mixed forest of Scots pine and Norway spruce (*Picea abies* (L.) Karst.). Bond-Lamberty et al. (2004a) demonstrated the effect of stand age on the contributions of R_r and R_h to R_s using a trenched-plot approach.

In a chronosequence of black spruce (*Picea mariana* (Mill.) BSP), Bond-Lamberty et al. (2004a) reported contributions of root respiration of 0, 35-40 and 5-15% in a recently burned site, a 21 year-old site and a 152 year-old site, respectively. Schuur and Trombore (2006) have reported values of 47-63% in a mature (80 year-old) black spruce stand in Alaska with isotope partitioning methods. In an 8 year-old North Carolinian loblolly pine (*Pinus taeda* L.) research site, the contribution of root respiration was 50-73% of soil respiration; however the authors acknowledge that the excised root method used may have overestimated this contribution due to limitations described above (Maier and Kress 2000). In a study by Epron et al. (1999b), the R_r contribution was 60% in a 30 year-old beech (*Fagus silvatica* L.) stand in northeastern France. This study was important as it corrected the respiration measurements for the accelerated decomposition of roots in the trenched plots. Furthermore, the authors noted the role soil moisture plays in trenched plot experiments and reported higher soil moisture content in the trenched plots due to a lack of evapotranspiration.

To illustrate the importance of correcting respiration values for increased decomposition of roots, I draw your attention to a study by Ohashi et al. (2000), in studying respiration components in a 10 year-old Japanese cedar (*Cryptomeria japonica* D. Don) plantation in southwest Japan. They reported that R_r contributed 40-70% of soil respiration, with a mean of 49%. However when corrected for root decomposition, the mean contribution was determined to be 57%, an increase of 8%. In a trenching experiment in central Japan, R_r contributed 32-48% and 27-39% of soil respiration, the first and second year after trenching, respectively, in a 40 year-old *Quercus crispula* Blume and *Betula ermanii*

Cham. forest (Lee et al. 2003). In a Brazilian study of a mature evergreen tropical forest, using a trenched plot experiment, Silver et al. (2005) reported that R_r was 24-35% of soil respiration in a clay soil. Interestingly, this same study found no difference between respiration in trenched plots and control plots in a sandy soil after 13 months and was not able to estimate the contributions of the different components of soil respiration using the trenched plot approach. A mass balance calculation estimated the R_r contribution as 28% and 35% in the clay and sandy soils, respectively.

The root exclusion method was selected for the current study. The root excluded plots were given one month to equilibrate after the disturbance caused by trenching, and special attention was given to calculations which accounted for the enhanced fine-root decomposition rate; which accounts for the two most widely criticized deficiencies of the method. Use of this method was also justified in the literature review by Bond-Lamberty et al. (2004b) who concluded that partitioning of soil respiration components using the root exclusion method yielded results that were not significantly different from results obtained using various other methods.

2.3. Effect of Soil Temperature and Moisture Content on Soil Respiration

Understanding the response of soil respiration to changes in environmental factors is of utmost importance in predicting the effects of global climate change on atmospheric CO_2 concentrations in centuries to come. The most important abiotic factors influencing the rate of CO_2 efflux from soils are soil temperature and moisture content, and thus both should be included in predictive models of soil efflux rates to enhance the accuracy of climate change simulations (Bowden et al. 1998). However, some studies have noted that temperature is the dominant environmental factor regulating seasonal variation in soil respiration and that soil moisture content is much less important (Raich and Schlesinger 1992; Yuste et al. 2003; Wan et al. 2005). It is important to note that it has been recognized that the various components of soil respiration (root respiration and associated mycorrhizal fungi, heterotrophic respiration of plant detritus and humified organic matter) have different sensitivities to changes in temperature (Boone et al. 1998).

Numerous studies have reported a positive correlation between soil CO_2 efflux and soil temperature, though the form of the relationship is still under debate (Lloyd and Taylor 1994). The relationship between soil temperature and respiration has been presented as a linear equation (Witkamp 1966), an exponential relationship (Buchmann 2000; Bekku et al. 2003; Wan et al. 2005), and an Arrhenius function (Howard and Howard 1979). Commonly, the exponential relationship is reported, and a Q_{10} value is calculated. The Q_{10} defines the dependence of soil CO_2 efflux to changes in soil temperature (Fang and Moncrieff 2001). For example, a Q_{10} of 2 indicates that for every 10 °C increase in soil temperature, soil respiration increases two-fold. Despite the various types of equations available to model the effect of temperature on soil respiration, it is widely accepted that soil CO_2 efflux is strongly related and highly sensitive to changes in soil temperature (Epron et al. 1999a; Fang and Moncrieff 2001). Bowden et al. (1998) reported an exponential increase in soil CO_2 efflux with increases in soil temperature for a mixed hardwood stand in north-central Massachusetts, USA with Q_{10} values of 2.03 and 2.39 for forest floor and mineral soil (0-10 cm), respectively. Boone et al. (1998) reported a higher Q_{10} of 3.5 for the bulk soil in a similar mixedwood stand in the same region and presented an exponential relationship of soil CO_2 efflux to soil temperature at 5 cm depth. A third study in the same experimental forest reported a mean Q_{10} of 3.9 (range of 3.4-5.6 across all sites) calculated from an exponential relationship which described 88% of the variation in soil CO_2 efflux. In four Norway spruce (*Picea abies* L. Karst.) stands in northeast Germany, an exponential relationship was also found to describe the relationship between soil CO_2 efflux and soil temperature at 5 cm ($r^2 = 0.75$-0.81) and generated Q_{10} values ranging from 2.39 in a 146-yr-old stand to 3.22 in an 87-yr-old stand (Buchmann 2000). A report from the Belgian Campine region noted Q_{10} values ranging from 1.93-2.39 and 2.45-4.80 in *Pinus sylvestris* L. and *Quercus robur* L. stands, respectively (Yuste et al. 2004). In a review of literature, Raich and Schlesinger (1992) reported a median Q_{10} value of 2.4 for studies from terrestrial ecosystems around the world.

Few studies have reported on the effect of soil moisture content alone on soil CO_2 efflux; most report an interaction between soil moisture content and soil temperature and their combined effect on soil CO_2 efflux. Orchard and Cook (1983) concluded that lack of soil moisture can limit soil CO_2 efflux by impeding the contact between microbial organisms and substrates and by inducing microbial dormancy and eventually death at low water potentials. Late summer values of CO_2 efflux were inhibited at low soil moisture contents (Epron et al. 1999a) in a beech forest in France. Lavigne et al. (2004) reported a reduction in CO_2 efflux of 25-50% in response to water stress in a balsam fir (*Abies balsamia*) forest in eastern Canada. Davidson et al. (2000) studied a site in Amazonia where temperature was not related to CO_2 efflux due to very little variation in temperature, which allowed the researchers to observe the effects of soil moisture content. They found that CO_2 efflux was higher during the rainy season than in the dry season; however the authors noted that CO_2 efflux was later inhibited on two occasions when soil was at near saturation after large rainfall events. An important point to consider was the approach of Davidson et al. (1998; 2000) to express soil moisture in terms of matric potential which is a better expression of the amount of water adsorbed to soil particles of different soil textures. This was found to be superior to expressions of water content on either a volumetric and gravimetric basis. Drought conditions caused rapid declines of CO_2 efflux in a mixed hardwood stand (Davidson et al. 1998); these findings corroborate results of Bowden et al. (1998) who reported reductions of CO_2 emissions at the highest and lowest soil moisture contents in a mixedwood stand in Massachusetts, USA. Wan et al. (2005) found that drought lowered soil CO_2 efflux irrespective of temperature, but that a model including both soil temperature and moisture content explained 82% of the variation in soil CO_2 efflux measurements. Soil CO_2 efflux was decreased by up to 50% when soil water content was limiting (below 15% v/v) and soil CO_2 efflux was insensitive to changes in soil temperature ($Q_{10} = 1.24$) at such low moisture contents (Yuste et al. 2003). Conant et al. (2004) reported similar results indicating that at low soil moisture contents, soil CO_2 efflux responded to changes in soil temperature but that the response was significantly smaller than at higher water contents.

2.4. Methods of Measuring Soil Respiration

There are four principle chamber methods that have been used to measure soil respiration, or CO_2 efflux. These include: 1) open-flow infrared gas analyzers (OF), 2) closed (static gas) chamber method (CC), 3) dynamic closed chamber method (DC), and 4) alkali absorption method (AA). In the OF system, ambient air is passed through a chamber that is placed on the soil surface and the CO_2 flux from the soil is calculated using the volume of the chamber, the flow rate of ambient air and the concentration difference between chamber inlet and outlet air (Nakayama 1990; Bekku et al. 1997). The CC method is much simpler. A chamber is placed on the soil surface and gas is sampled periodically with a gas tight syringe and CO_2 concentration is determined in the laboratory, usually by gas chromatography (Nakayama 1990; Bekku et al. 1997). The efflux is calculated from the rate of increase of CO_2 during the sampling time interval (Nakayama 1990). The DC system is similar to the CC method. A chamber connected to a gas analyzer is placed on the soil surface. Air is circulated to the analyzer and then returned to the chamber. Efflux is computed as the increase in CO_2 concentration over time. This differs from the OF system because air taken from the chamber is returned and the unit is sealed preventing ambient air from entering the system. The AA method is a variation of the CC method where CO_2 accumulating in a chamber is absorbed in a caustic solution. Determination of CO_2 is done by titration in the laboratory.

In a comparison of the four chamber methods, Bekku et al. (1997) reported efflux rates 1.3 to 9 times larger using the AA method compared to the OF, DC and CC methods. Furthermore, the methods were tested in the laboratory where known quantities of glucose were used as substrate for microorganisms and C loss from the glucose was measured by weighing samples. The measured efflux rates were used to provide estimated glucose respired (EGR) while weight loss was termed actual glucose respired (AGR). The AA method EGR was 1.3 times the AGR, while the OF, DC and CC EGR estimates were 0.95, 0.95 and 0.94 of AGR, respectively (Bekku et al. 1997). The authors concluded that the AA method was not reliable in providing close approximations of actual soil respiration. Contrary to these findings, Rochette et al. (1992) reported that the AA method consistently resulted in underestimation of soil efflux compared to the DC method and that differences between the two techniques were greater as fluxes increased. Raich et al. (1990) reported no consistent differences between the AA and CC methods. Emissions of soil CO_2 occur primarily by diffusion; Fick's first law dictates that efflux is proportional to, and dependent on, the concentration gradient between the soil (air-filled pore space) and the chamber air (Nakayama 1990; Welles et al. 2001; Davidson et al. 2002). The concept of changing the CO_2 concentration gradient between the soil and the chamber air is central to limitations of applicability of all chamber methods. Using this concept, Bekku et al. (1997) and Rochette et al. (1992) were able to hypothesize the reasons for the shortcomings of the AA method. Bekku et al. (1997) explained that as the CO_2 in the chamber is absorbed into solution, the CO_2 concentration in the chamber air decreases, which increases the concentration gradient. This increased gradient would inherently increase efflux from the soil and lead to overestimation of the actual efflux. Rochette et al. (1992) explained the efflux underestimation of the AA method as a reduction or decrease in CO_2 diffusion into solution resulting in an accumulation of CO_2 in the chamber air. This results in a decreased concentration gradient between the soil and the chamber air, and therefore a reduction in the efflux rate. Norman et al. (1997) reported that the CC method tended to underestimate efflux compared to the DC method, and Bekku et al. (1995) concluded that efflux rates from the CC and OF methods were not significantly different. Nevertheless, numerous studies have concluded that the CC method is sensitive to accumulation of CO_2 in the chamber, which negatively affects the concentration gradient and suppresses efflux from the soil surface (Nakayama 1990; Bekku et al. 1997; Welles et al. 2001). The DC method is superior to the CC method since it scrubs the air in the chamber to below ambient levels prior to commencing a measurement, thus avoiding complications of altering the concentration gradient (Davidson et al. 2002). Davidson et al. (2002) showed that non-steady state measurement systems, such as the CC method, will usually cause an underestimation of soil efflux of 0-15%. However, short sampling time intervals (2-4 minutes) can be used to avoid impacting the concentration gradient (Bekku et al. 1997). Norman et al. (1997) warned that to obtain a reliable estimate of efflux from the CC method, a small fan must be used to properly mix the air in the chamber. Pongracic et al. (1997) concluded that the use of a fan for mixing in the AA method may have helped overcome the differences observed between the AA and DC methods. One method used to mix chamber air was pumping with the sampling syringe prior to sampling (Norman et al. 1997). Bekku et al. (1995) proved that the sampling volume in the CC method can also significantly affect efflux rates. The authors concluded that if too much volume was sampled from the chamber, the decrease in air volume in the chamber would create mass flow of highly concentrated CO_2 from the soil causing an overestimation of the actual flux. The OF method is limited due to pressure differences/anomalies between the atmosphere and the chamber caused by the flow of air through the system (Norman et al. 1997). Furthermore, the effect of pressure is different if the air is pushed (pressure) or sucked (suction) through the chamber (Nakayama 1990). Suction of air from the chamber causes highly concentrated soil air to be drawn from the soil pore space, greatly increasing the efflux, while pushing air through the chamber suppressed efflux (Welles et al. 2001). Results from Kanemasu et al. (1974) and Nakayama (1990) are consistent with these findings as they reported much higher CO_2 efflux when the gas stream was sucked through the chamber. Fang and Moncrieff (1998) reported that a pressure change as little as -1 Pa could cause an order of magnitude increase in the CO_2 efflux rates using a DC method. Nakayama (1990) reported similar results using the OF system to quantify N_2O fluxes; N_2O efflux was increased by a factor of 10 when a pressure change of -1 Pa was observed. New designs of chambers now include a narrow tube linking the chamber headspace to the atmosphere to equilibrate the pressure (Norman et al. 1997; Welles et al. 2001). Finally, all chamber methods may cause soil disturbance from placing the chamber into the soil and thus affecting the soil respiration measurement. Polyvinyl chloride (PVC) collars fitted to the chambers are commonly used to obtain a good seal with the soil surface; however efflux measurements made immediately after collar insertion tended to be larger than those taken longer after collar insertion (10-30 minutes, Norman et al. 1997), a phenomenon referred to as CO_2 flushing (Wang et al. 2005). Norman et al. (1997) reported that 10-30 minutes were needed for efflux to stabilize after collar insertion. Wang et al. (2005) illustrated the importance of collar insertion depth in affecting soil CO_2 efflux rates. Interestingly, the authors reported reduced soil efflux when collars were inserted 3, 5 and 8 cm into the soil compared to an insertion depth of 0.3 cm. A typical collar insertion reported in the literature is 2-3 cm (Norman et al. 1997; Lavigne et al. 2003). The difference was linked to a reduced contribution of fine root respiration to soil respiration due to severed roots from collar insertion and recommendations were made to consider this effect especially in forests with superficial root systems (Wang et al. 2005). Despite the variability between the different methods, Nakayama (1990) concluded that reasonable values of soil CO_2 efflux can be obtained using both the closed and open chamber methods.

The CC method was chosen for the current study for numerous reasons. One advantage of the CC method is that collection of gas samples and subsequent analysis allows for detection of three trace gases: carbon dioxide, methane and nitrous oxide. Davidson et al. (2002) reported that the DC method is superior to the CC method; however availability of a LI-COR 6400 system with the 6400-09 soil respiration attachment could not be guaranteed for all sampling dates and method consistency was crucial to provide comparable results. However, the LI-COR system may have been useful on one or two occasions to provide a comparison to the results obtained by the CC method. Finally, two comparison studies verified the accuracy of measurements taken with the CC method: 1) Bekku et al. (1995) concluded that the CC and OF methods provided similar efflux results and 2) Bekku et al. (1997) concluded that the CC, DC and OF methods all reported similar efflux results. In the current study, samples were collected at times 0, 5, 10 and 20 minutes; however the CO_2 concentrations at times 0 and 5 were selected for calculation of soil CO_2 efflux to avoid underestimation of the efflux caused by changes in the CO_2 gradient during longer sampling intervals. The chamber system used did not allow for the use of a fan to mix the sample air inside the chamber; therefore slow pumping of the sampling syringe was used to provide better quality samples.

2.5. Effect of Land-Use Conversion

2.5.1. Effect of Agricultural Practices on Carbon Cycling

Lal et al. (2004) reported that shortsighted farming practices have led to a loss of 78 ± 12 Gt of C from the world's soils. The loss of C from cropping soils can be attributed to a large reduction in inputs (most of the aboveground biomass is harvested), an increase in decomposability of crop residues and the enhanced access to soil C previously inaccessible to soil microorganisms due to physical breakdown of soil aggregates from tillage (Post and Kwon 2000). Lal (2002) also concluded that mineralization of C from aggregate destruction led to the loss of soil C. Furthermore, he added that losses are also due to leaching and translocation of dissolved organic C and accelerated erosion by water and wind due to soil exposure in the cropping systems.

Numerous studies have reported large losses of soil C resulting from agricultural crop production. Houghton (1999) reported a net flux of 124 Gt of carbon to the atmosphere from all land conversion activities from 1850 to 1990, and concluded that 68% of that flux was generated from croplands. In the Georgia Piedmont in USA, C storage in soils declined from a pre-settlement value of 386 x 10^6 t (0.386 Gt) to only 40 x 10^6 t (0.04 Gt) at the height of agriculture in the region (Sharpe et al. 1981). However, post World War II reforestation had increased C stores to 112 x 10^6 t (0.112 Gt) by 1972. Forest clearing resulted in decreases of 35, 50 and 15% in soil C in tropical, temperate and boreal regions, respectively; nonetheless all regions were found to have lost 50% of their soil C stores before reaching a new equilibrium when cultivation took place after deforestation. A similar estimate of C loss after clearing and cultivation was reported by Dalcourt et al. (1980) where they found a 40% decrease in soil C storage in southeastern USA. Similar soil C decreases of 42% (forest to crop, 37 studies) and 59% (pasture to crop, 97 studies) were reported by Guo and Gifford (2002) in a review of the literature. More recently, estimates of soil C loss reported for the northwest USA and western Canada averaged 34 ± 14% for soil depths $\leq$ 30 cm due to land conversion to cropping systems (Liebig et al. 2005). A more conservative estimate of C loss of 20% was reported by Hanson (1993) and Mann (1986) prior to a new C cycle equilibrium being reached. Hanson (1993) concluded that the loss was from the top 30 cm of soil and Mann (1986) found that the greatest losses occurred in the first 20 years after land conversion to cropping. Losses of up to 50% from surface soils after 30-50 years of cultivation was reported by Post and Kwon (2000), while Lal (2002) reported that soils reached a new equilibrium with only 30-50% of the original soil C remaining after approximately 50 years. Houghton (1999) also reported a large soil C depletion of 50% in the top 20-30 cm due to cropping.

2.5.2. Conversion of Land from Agricultural Row Crop to Plantations

The impact of planting hybrid poplars on carbon dynamics and storage on previously farmed land is largely unknown for the boreal region of the Canadian prairies. However, due to the large losses of soil C from agricultural row crop production, agricultural lands are believed to be a major potential sink for CO_2 and could absorb vast quantities of C if trees were re-introduced (Albrecht and Kandji 2003). The plantation establishment period has been found to be a time marked by a net loss of C to the atmosphere (Hansen 1993; Grigal and Berguson 1997; Paul et al. 2002; Wang et al. 2006). These studies reported an initial period of carbon loss ranging from 5 to 12 years after plantation establishment before a gradual recovery of soil carbon and subsequent accumulation as C inputs eventually exceeded C outputs. Hansen (1993) hypothesized that the carbon loss during the initial plantation establishment originates from rapid decomposition of organic residues from the exposed tilled mineral soil surface; moreover, most of the early carbon loss was from the 0-30 cm soil layer. Paul et al. (2002), in a review of literature, reported similar trends: soil surface carbon in the 0-10 cm and 0-30 cm intervals was found to decrease during the first five years of plantation establishment and recover to levels similar to what was found in the previous agricultural system after approximately 30 years. Vesterdal et al. (2002) reported that the decline in soil C in young stands may be attributed to low inputs from aboveground biomass and faster ongoing decomposition of materials from the previous agricultural activity; Paul et al. (2002) also concluded that during the first three years of establishment, very little input of C from aboveground were available to the surface (0-30 cm) of the soil. Vesterdal et al. (2002) echoed this finding by concluding that it took about 10 years for a forest floor to develop in regenerating *Quercus robur* L. and Norway spruce (*Picea abies* (L.) Karst) forests. Despite the initial decrease in soil C, Paul et al. (2002) reported that during the first 10 years of plantation growth, soil C increased by 0.87% yr^{-1} in the 0-10 cm interval and by 1.88% yr^{-1} in the 0-30 cm interval. More recently, Wang et al. (2006) found that a larch (*Larix olgensis* (Henry)) plantation in northeastern China gained 7.65 Mg C ha^{-1} after 30 years in the 0-30 cm surface soil. In hybrid poplar plantations, soil C accretion exceeded that of adjacent agricultural row crops by 1.63 Mg C ha^{-1} yr^{-1}, and plantations 12-18 years old had 24.4 Mg C ha^{-1} more soil C than adjacent row crops (average 15 years old, Hansen 1993). Hanson (1993) attributed the gain in soil C to root growth in the 30-50 cm zone of the soil. In a land conversion study of sugarcane agriculture to eucalyptus plantations in Hawaii, soil C was found to increase with plantation age from 6.45 to 9.98% after 10 years of plantation growth (Zou and Bashkin 1998). In a review of 29 studies that monitored soil C changes when croplands were converted to plantations, Guo and Gifford (2002) reported an average increase of soil C of 18%.

Some work has also shown that a C gain is not always the case in plantation forestry. In a conversion of sugarcane to *Eucalyptus saligna* (Sm.) in Hawaii, no change in soil C was found in the 0-45 cm soil interval during the first 8 years of plantation (Binkley et al. 2004). Furthermore, some noted that the largest contribution to soil C was in the form of coarse roots. Bashkin and Binkley (1998) found that conversion from sugarcane to *Eucalyptus saligna* (Sm.) produced a gain of 11.5 Mg C ha^{-1} in the 0-10 cm surface soil which was balanced by a loss of 10.1 Mg C ha^{-1} in the 10-55 cm soil interval after 10-13 years, resulting in no net increase in soil C. The loss of soil C in the lower soil horizons was attributed to the change in land management when converting the land-use from sugarcane to plantation: agricultural practices homogenize soil C content to greater depths in the soil; however this redistribution no longer exists once a plantation is established. The result is depletion of soil C in the deeper soil layers due to the lack of C redistribution. Afforestation of arable land with oak and Norway spruce was found to sequester 2 Mg C ha^{-1} and 9 Mg C ha^{-1} in the forest floor after 29 years (Vesterdal et al.

2002). The authors also reported an increase in soil C in the 0-5 cm surface, but a decrease in the 5-15 and 15-25 cm soil layers with plantation age. There was no net C sequestration in soil as the accumulation of forest floor C was offset by the loss of soil C in the lower mineral soil (5-25 cm) after 30 years (Vesterdal et al. 2002).

2.5.3. The Kyoto Protocol and Hybrid Poplar Plantations

The Kyoto Protocol was drafted in 1997 and sets quantitative commitments for countries to limit greenhouse gas (GHG) emissions (West and Marland 2002). This international agreement also recognizes that emissions can be offset by the removal of CO_2 from the atmosphere by an increase in the net carbon stocks of the biosphere (West and Marland 2002). Sources and sinks are limited to afforestation, deforestation and reforestation programs since 1 January 1990 (Smith 1999). In Canada, tree plantations established on land that was under agricultural use prior to 1990 qualify as an afforestation activity under the Kyoto agreement and thus are named "Kyoto forests". Recently, in the province of Saskatchewan, the provincial government announced plans to expand the agroforestry sector by planting 1.62 million hectares of agricultural land into tree plantations over the next 20 years (Haverstock 2005), of which the majority will likely be hybrid poplars. Alberta-Pacific Forest Industries Inc. (Al-Pac) is currently leasing and planting 1200 hectares of marginal agricultural land per year in north-central Alberta with the goal of planting 25 000 hectares of land into hybrid poplar plantations by the year 2020. Despite the lack of research on soil C processes in hybrid poplar plantations, as discussed in the introduction, the Canadian commitment to emission reduction targets under the Kyoto Protocol calls for new research into alternative solutions for greenhouse gas mitigation; one such alternative is the planting of hybrid poplar plantations. Furthermore, with the commitment of vast areas of new plantings, as in the province of Saskatchewan and at Al-Pac, we must achieve a clear understanding of the impacts of tree plantations on the C cycle and potential for C sequestration. In light of the demand for new knowledge, the current research will provide an understanding of the initial impacts of hybrid poplar plantation establishment on C cycling. Moreover, this thesis will examine the factors contributing to soil respiration which will be crucial to understanding the potential impacts of hybrid poplar plantation establishment on C cycling and climate change.

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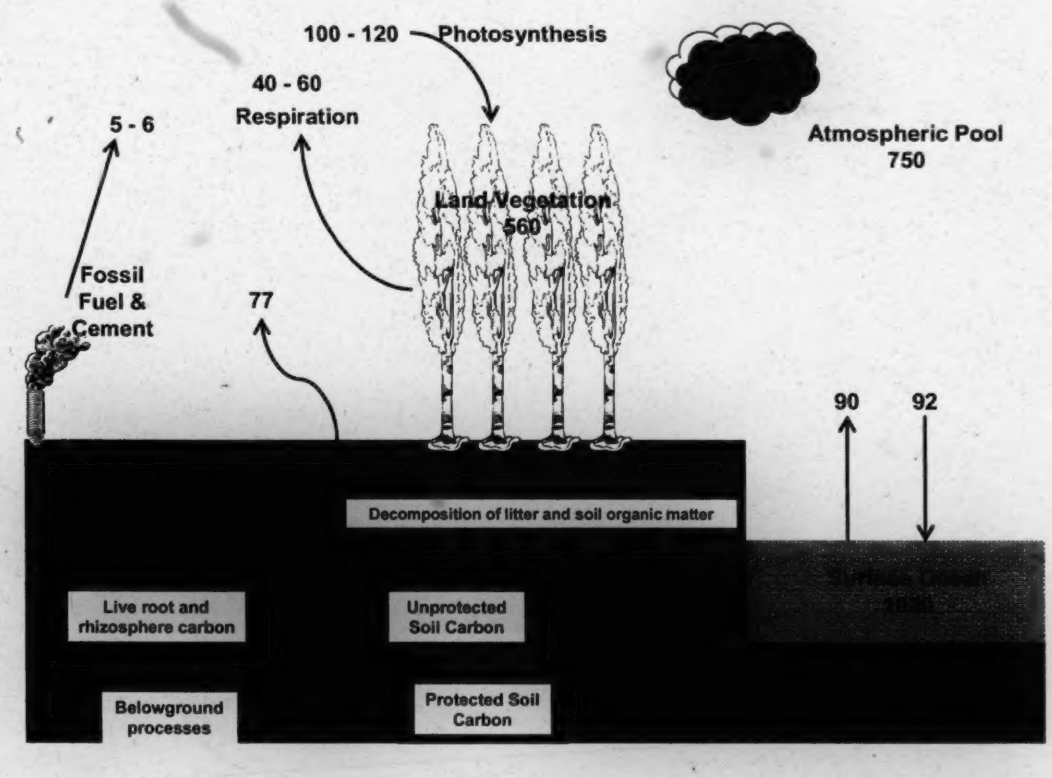
Figure 2.1. Carbon cycle with emphasis on the soil carbon processes. Pools and fluxes are in 10^{15} g C yr^{-1}. Modified from Schlesinger and Andrews (2000) and Hanson et al. (2000).


100 - 120
Photosynthesis
40 - 60
Respiration
5 - 6
Atmospheric Pool
750
Land Vegetation
560
Fossil
Fuel &
Cement
77
90
92
Decomposition of litter and soil organic matter
Surface Ocean
1020
Live root and
rhizosphere carbon
Unprotected
Soil Carbon
Belowground
processes
Protected Soil
Carbon

3. THE EFFECT OF LAND-USE CONVERSION ON EMISSIONS OF CO_2: AGRICULTURE TO HYBRID POPLAR PLANTATIONS

3.1. Introduction

A rapid and unprecedented increase of atmospheric carbon dioxide (CO_2) concentration (which is the main contributor of the greenhouse effect) in recent decades has led to concerns about changes to the earth's climate (Ingram and Fernandes 2001). Countless research projects studied the mechanisms controlling CO_2 exchanges between the land and ocean systems and the atmosphere in trying to find ways to mitigate the effects of anthropogenic sources of greenhouse gas (GHG) emissions (see Rustad et al. 2000; Schlesinger and Andrews 2000; Vandenbygaart et al. 2004; White and Kurz 2005). The potential to enhance the biotic component of the carbon (C) cycle is key to reducing atmospheric CO_2 and has received much attention; moreover, regenerating tree plantations may be an important carbon sink by sequestering carbon in two forms: in above and belowground plant biomass and in soils through litter deposition and root decomposition (IPCC 1996). To date, farming practices have resulted in a loss of an estimated 78 ± 12 gigatons (Gt) of carbon from soils (Lal et al. 2004); therefore agricultural lands are believed to be a major potential sink for CO_2 and could absorb vast quantities of C if trees were re-introduced (Albrecht and Kandji 2003). In Canada and many other countries that have ratified the Kyoto protocol, afforestation[2] projects are a means of rapidly sequestering vast quantities of C in wood biomass; however often overlooked is the potential to replenish the soil C stocks as plantations are usually established on formerly cultivated land used to plant row crops, that have in many cases lost 30% of there soil C (Grigal and Berguson 1998).

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[2] Afforestation is defined under the Kyoto Protocol as the direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding and/or the human-induced promotion of natural seed sources (Governmant of Canada 2003).

Net ecosystem production (NEP) informs us of the movement of C through an ecosystem; an ecosystem can either have a net loss (source), or a net gain (sink) of C. NEP is governed by two important fluxes: photosynthesis and respiration (Trumbore 2006). It is important to note that soils reach equilibrium in terms of soil C content which is controlled by the inflows and outflows of the system that can be altered by land-use change, resulting in an eventual new equilibrium (Guo and Gifford 2002). For example, L [illegible] (2002) reported that soils converted to cultivation reached a new equilibrium with only 30-50% of the original soil C after approximately 50 years.

Most studies addressing C in tree plantations are focused on the C balance of an entire rotation, which can vary from 6 years in tropical locations to more than 30 years depending on the regional climate, length of growing season and intended use of the biomass. Paul et al. (2002) reported a decrease of soil C by 3.46% in the <10 cm layer during the first five years after plantation establishment in a review of 43 published and unpublished studies. This high rate of decrease declined and plantations recovered to initial soil C levels by age 30 (Paul et al. 2002). It must be noted that this study did not include the forest floor in the calculations of soil C, which can be a critical component of C sequestration in plantations. For example, Vesterdal et al. (2002) found that forest floors in Denmark sequestered 2 Mg C ha^{-1} in oak stands and 9 Mg C ha^{-1} in spruce stands, over a 29 year period, which offset the amount of C lost from mineral soil. Soil C accretion under 12- to 18-year-old hybrid poplar plantations in the north central United States was 1.63 Mg C ha^{-1} yr^{-1} more than in adjacent agricultural soils; at an average age of 15 years, the plantations has accumulated 24.4 Mg C ha^{-1} more than adjacent row crops (Hansen 1993). In their review of the literature, Guo and Gifford (2002) found that a land-use change from cropping system to plantation resulted in a soil C increase of 18% (29 observations). Furthermore, Grigal and Berguson (1998) reported an equality of soil C between plantation and previous land-use after approximately 15 years. These various studies illustrate the C sequestration potential of soils in various regions; nevertheless, little work has been done to understand the dynamics of C in plantations during the first year after land conversion. Given that the largest loss of C in a plantation occurs during the early establishment phase, it is important to understand the principal drivers of this augmented C loss. Furthermore, a better comprehension of the dynamics in a young plantation may provide land-owners with management options to reduce such a loss.

Soil C losses are directly related to the oxidation of C which is subsequently released to the atmosphere as CO_2. In a study of land conversion from sugarcane to *Eucalyptus saligna* (Sm.), Bashkin and Binkley (1998) reported an increase of soil C in the surface layer of 11.5 Mg C ha^{-1} which was offset by a loss of 10.4 Mg C ha^{-1} in the lower soil layers after 10 to 13 years. They concluded that the net effect of afforestation on soil C in cultivated lands was not only a result of the new C gained from the new land-use, but also from the C lost due to a reduction of inputs into the 5-40 cm soil depth. Tillage in the agricultural sugarcane operation distributed C into the lower profile; no tillage was used after afforestation, therefore reducing the inputs of C (Bashkin and Binkley 1998). Similarly, Hansen (1993) found that C sequestration in older plantations will eventually compensate for the early losses due to land conversion. He reported a net addition of soil C after 6 to 12 years in hybrid poplar plantations. In hybrid poplar plantations in Minnesota, USA, soil C lost in the first year after conversion to plantation was equal to the loss of C under the previous land-use (Grigal and Berguson 1998). These same authors also found that this loss of soil C declines to 75% of the soil C loss in the original land-use by the fifth year primarily due to mulching, shading and the lack of soil disruption in the plantation.

The purpose of this study was to determine the short-term response of a previously agricultural system to the establishment of a hybrid poplar plantation in terms of potential changes in CO_2 emissions. I hypothesized that soil respiration rates would be higher in agricultural plots as compared to newly established plantation plots due to the lack of fresh C inputs in the hybrid poplar plantation, and that soil C in the surface horizons would be lower in the hybrid poplar plantations for the same reason.

3.2. Materials and Methods

3.2.1. Site description

This study was conducted at the Alberta-Pacific Forest Industries Inc. (Al-Pac) pulp mill site near Boyle (54° 49' N, 113° 31' W), Alberta, about 200 kilometers north of Edmonton, Canada, from June to October 2005 (Fig. 4.1). The site is 626 meters above sea level, with a mean (1971-2000) annual temperature of 2.1°C and mean annual precipitation of 503.7 mm, of which one third falls as snow (Environment Canada 2004). The climate is continental with warm summers and cold winters which provides an approximate growing season of 175-180 days (Alberta Agriculture, Food and Rural Development 2003). The area is characterized as having an undulating landscape within the Alberta Plains which is dominated by till deposits from the LaBiche Formation (Kjearsgaard 1972). Glacial streams flowing from the ice mass and rivers flowing into glacial lakes deposited fluvio-glacial sands and gravels throughout the landscape (Kjearsgaard 1972). The dominant tree species in native forest in the Mixedwood Section (within which this study is located, Moss 1955) are trembling aspen (*Populus tremuloides* Michx.), white spruce (*Picea glauca* (Moench) Voss), paper birch (*Betula papyrifera* Marsh), and balsam poplar (*Populus balsamifera* L.) (Kjearsgaard 1972). Agricultural activities in the latter half of the 20th century dramatically changed the landscape as numerous farms were established throughout the area. The plots studied occur on Gleysolic soils (Table 2.1, Soil Classification Working Group 1998), which is consistent with the Soil Survey of the Tawatinaw Mapsheet (83-I, Kjearsgaard 1972). The research plots from this experiment are all established on previously cleared and cultivated, marginally productive land.

3.2.2. Experimental design

The experiment used a Randomized Complete Block Design with three blocks, and two treatments: 1) Walker poplar (*Populus deltoides* x *Populus x petrowskyana* var. Walker) plantation and 2) barley (*Hordeum vulgare* L. var Argyle, Fig. 3.2). In the summer of 2004, all six plots were seeded to barley and harvested in September 2004. All plots were disked on 8 June 2005 to prepare for planting and seeding. On 10 June 2005, the Walker poplar trees were planted at an operational spacing of 3 x 3 m using over-winter dormant stock (plugs): this means in the year prior to planting, cuttings of Walker trees were propagated and grown in the greenhouse in Styrofoam blocks, placed in an industrial freezer for the winter and thawed the day of planting. The barley plots were seeded on 7 July 2005 and harrowed (to cover seeds after sowing) on 8 July 2005. The barley plots were established relatively late in the growing season due to high precipitation and hence reduced access to the site for the seeding equipment. Soil core samples were collected on 8 June, 7 July and 9 August 2005 to determine soil chemical properties and nutrient contents as described below. All sampling was completed a minimum of 8 m inside the treatment plot boundaries to negate any edge effect.

3.2.3. Soil temperature and volumetric water content

All plots were monitored for soil temperature at 10 cm with type T (copper-constantan) thermocouples (Omega Engineering, Montreal, Canada) and data-logged with Campbell Scientific CR10X dataloggers (Campbell Scientific, Inc., Logan, UT, USA). Soil temperature was measured and recorded every ten minutes, the daily minimum and maximum and hourly temperature averages were also recorded. Volumetric water content was measured using Campbell Scientific CS616 water content reflectometers (Campbell Scientific, Inc., Logan, UT, USA). The reflectometers were inserted horizontally using a CS615 installation kit at (10 cm depth) in an exposed soil profile. The hole was then backfilled with original soil material in its natural order to minimize disturbance. The water content reflectometer derives the water content information based on the probe sensitivity to the dielectric constant of the medium surrounding the probe rods. The CS616 water content reflectometers have an accuracy of ±2.5% and a resolution of approximately 0.1% (Campbell Scientific, Inc. 2002).

3.2.4. Soil respiration (R_s)

Respiration rates were derived from greenhouse gas samples collected using a static chamber technique on 8 June, 23 June, 7 July, 19 July, 9 August and 22 August 2005. Two plastic soil collars fitted to the Hutchinson chambers (Fig. 3.3, headspace height = 10 cm, volume = 0.00104 m^3) were randomly placed in each of the three Walker poplar and barley plots. The collars were pushed approximately 3 cm into the soil and were placed 24 hrs prior to sampling to avoid error induced from soil disruption which occurs when placing the collars in the soil. Air samples were collected by gas-tight syringe prior to placing the chamber over the collars (ambient condition) and 5, 10 and 20 minutes after placing the chamber over the collar through a rubber septum and stored in evacuated 10-mL soda glass Isomass Exetainers®. Gas samples were collected on fair weather days to avoid the confounding effect of increased soil respiration in response to increases in soil moisture. The vials were over-pressurized by injecting a 20 mL gas sample to ensure a positive pressure for successful analysis on a Varian CP-3800 gas chromatograph (GC, Varian Canada, Mississauga, Canada) equipped with three detectors: an Electron Capture Detector (ECD) for quantification of nitrous oxide (N_2O), a Flame Ionization Detector for methane (CH_4) detection and a Thermal Conductivity Detector (TCD) for carbon dioxide (CO_2) determination.

In December 2004, a cross-laboratory calibration of standards was completed with Agriculture and Agri-Food Canada in Lethbridge, Alberta. Fourteen laboratories from across the Canadian prairie region submitted standards to be calibrated against standards developed by the National Oceanic and Atmospheric Administration of the United States Department of Commerce. This calibration was primarily aimed at improving N_2O detection as it is the most troublesome of the three greenhouse gases discussed above to quantify. Once this calibration was complete, the GC was routinely re-calibrated on a bi-weekly basis to ensure proper detection of the trace gases. A five point calibration was used with three replicate samples at each calibration level. Calibration was deemed acceptable only with an r^2 greater than 0.99. A sample calibration curve for the TCD is presented in Figure 3.4.

Gas concentrations determined by GC for the 0, 5, 10 and 20 minute samples were then transformed into respiration rates using Equations 1 (Nakayama 1990) and 2:

$$Efflux = \frac{\Delta C * T * V}{\Delta t * A} = \frac{\Delta C * T * h}{\Delta t} \qquad \text{Equation 1}$$

Where ΔC = change in CO_2 concentration in the selected time interval (μmol mol^{-1})

T = temperature adjustment for molecular volume of gas (mol m^{-3})

V = volume of static gas chamber (m^3)

A = area of ground covered by static gas chamber (m^2)

h = height of Hutchinson chamber (m)

Δt = time interval (s)

$$T = 44.6 \text{ mol m}^{-3} * 273.15 \div (273.15 + \text{Actual Air Temperature}) \qquad \text{Equation 2}$$

The concentrations of CO_2 at time zero and the 5 min interval were selected to compute the respiration values to avoid the plateau effect which develops when CO_2 concentrations within the chamber become too high and the slope of CO_2 increase over time becomes non-linear due to differences in the concentration gradient between the soil and the air in the chamber (Fig. 3.5). The average soil respiration of the 6 sampling dates for each treatment, barley and Walker poplar, were used to calculate an estimate of total C loss through soil respiration from 1 May to 30 September 2005.

3.2.5. Walker poplar and barley field measurements and net primary productivity

The Walker poplars were planted using a 3 x 3 m completely symmetrical grid. This spacing provides a tree density of 1111 stems ha^{-1}. In each Walker poplar plot, 350 trees were planted, for a total of 1050. Of these, 112 were sampled in each plot for biomass calculation. Tree height and root collar diameter (RCD, at the soil-tree stem interface) were measured. RCD was measured using a caliper and tree height was measured with a surveying rod. Tree volume (Avery and Burkhart 1994) and biomass were calculated using the following equations:

$$\text{Tree Volume } (\text{m}^3) = \left(\frac{\pi r^2}{3}\right) \times height(m) \qquad \text{Equation 3}$$

$$\text{Tree Biomass (kg)} = \text{Tree Volume } (\text{m}^3) * \text{Wood Density } (\text{kg m}^{-3}) \qquad \text{Equation 4}$$

The wood density value used was 358 kg m^{-3} (Morrison et al. 2000). Tree biomass accumulation for the 2005 growing season (kg ha^{-1}) for the Walker poplar plots was calculated as the difference between biomass on 8 June 2005 (planting date) and biomass at the end of the growing season. These values were scaled up by multiplying by the tree planting density (assuming 100% survival). Fresh weights were converted to dry weights using data collected from destructive sampling of 12 trees dried at 65 °C until samples reached a constant weight. Conversion of biomass production from kg ha^{-1} to kg C ha^{-1} was calculated from nutrient analysis on 18, 1-yr-old Walker poplars which had a mean C content of 49.98 ± 0.25% (Arevalo, *pers. comm.*). C accumulation from root production was calculated as a 1:1 ratio between root and shoot (Cao and Ohkubo (1998) reported root:shoot ratios of saplings of 8 species of which a ratio of 1:1 was common). Net primary production was calculated as the sum of tree aboveground biomass and root biomass.

Barley biomass was determined from the weight of bales in each of the three barley plots. Sub-samples were dried at 65 °C for 48 hrs to determine moisture content. Barley stubble left on the ground after harvest was also sampled using a 0.25 x 0.25 m quadrant; these samples were dried at 65 °C for 48 hrs. Biomass removed during harvest was estimated at 40%: therefore 60% of biomass was considered straw remaining on site (Equation 5). Root and residue C was estimated as 59% of straw biomass as per Campbell et al. (1995, Equation 6). NPP (kg ha^{-1}) was calculated by scaling up from plot size measurements to a per hectare basis and summing the straw and residue components (Equation 7). Conversion of NPP in kg ha^{-1} to kg C ha^{-1} was calculated using a mean C content of 43.6% (Biscoe et al. 1975).

$$BarleyStraw(kgCha^{-1}) = BarleyBiomass(kgCha^{-1}) \times 0.60 \qquad \text{Equation 5}$$

$$Barley\,\mathrm{Re}sidues(kgCha^{-1}) = BarleyStraw(kgCha^{-1}) \times 0.59 \qquad \text{Equation 6}$$

$$BarleyNPP(kgCha^{-1}) = BarleyStraw + Barley\,\mathrm{Re}sidues \qquad \text{Equation 7}$$

3.2.6. Laboratory analysis

Air-dried soil samples were used to determine total organic C and N concentrations for each classified soil horizon in the six research plots. Total organic C (TOC) was determined using a Carlo-Erba NA1500 CNS elemental analyzer (Carlo Erba Instruments, Milano, Italy). Dissolved organic C (DOC) and dissolved organic N (DON) concentrations in the 0-10 and 10-20 cm depth increments were determined for the 8 June, 7 July, 9 August, 14 September and 16 October sampling dates using the procedure described below. Air-dried mineral soil samples homogenized by a 2-mm sieve were extracted with distilled water using a 5:1 (water:soil) ratio and subsequently analyzed on the Shimadzu TOC-V CSH/CSN Total Organic Carbon Analyzer (Shimadzu Corporation, Kyoto, Japan).

Particle-size analysis was completed to determine soil texture for each soil horizon of the six research plots using the hydrometer method (Sheldrick and Wang 1993) with samples containing more than 5% total organic carbon receiving hydrogen peroxide pre-treatments (Day 1965). Soil pH was also determined on air-dried soil samples for all soil horizons with water and 0.1 M calcium chloride ($CaCl_2$) solution at a ratio of 1:1 (10 g soil: 10 mL deionized water or $CaCl_2$, Table 3.2). Samples were mixed in Dixie® cups (small paper cups with a wax lining), allowed to stand for 10 minutes as per Thomas (1996) and analyzed with a Piccolo® 2 portable pH electrode (Hanna Instruments, Laval, Canada).

Microbial biomass C (MB-C) and N (MB-N) were determined on fresh soil samples using the chloroform fumigation-extraction method (Voroney et al. 1993) on 8 June, 7 July, 9 August, 14 September and 17 October 2005 for the 0-10 and 10-20 cm mineral soils. Three 20 g samples were weighed; two were placed in 100-mL glass bottles, and the third in an aluminum weighing container for water content determination. Soil samples used to analyze the water content were dried in an oven at 105°C for 48 hours, cooled and reweighed. The water content was then calculated using Equation 5 (Kalra and Maynard 1991):

$$WS(WaterContent,\%) = \frac{(SoilWetWeight - SoilDryWeight)}{SoilOvenDryWeight} * 100 \qquad \text{Equation 8}$$

One set of the remaining samples received a fumigation treatment. The sample jars were left open and placed in a desiccator. A 100 mL beaker with 50 mL of ethanol-free chloroform ($CHCl_3$) and some boiling chips was placed in the desiccator which was then sealed and evacuated until the $CHCl_3$ was boiling vigorously for one minute. The desiccator was then sealed under vacuum and covered with a black plastic garbage bag to keep the samples in darkness for 24 hours. The vacuum was then released and the excess $CHCl_3$ discarded. Six evacuations were used to remove the residual $CHCl_3$ from the soil samples prior to extraction. For both the fumigated and unfumigated samples, 40 mL of 0.5 M K_2SO_4 was added. The samples were then placed in a rotary shaker for one hour, filtered through a Fisherbrand® Q2 filter paper, and the filtrate frozen (-18°C) until analysis. The filtrate was analyzed for total organic carbon (TOC) and total organic nitrogen (TON) with a Shimadzu TOC-V CSH/CSN Total Organic Carbon Analyzer (Shimadzu Corporation, Kyoto, Japan).

The total amount of extractable C and N in the fumigated (O_F) and unfumigated (O_{UF}) soil samples:

$$OC_F, OC_{UF}(\mu g \cdot g^{-1} soil) = extractableC(\mu g \cdot L^{-1}) \times \frac{VS(mL)}{MS(g)} \qquad \text{Equation 9}$$

$$ON_F, ON_{UF}(\mu g \cdot g^{-1} soil = extractableN(\mu g \cdot L^{-1}) \times \frac{VS(mL)}{MS(g)} \qquad \text{Equation 10}$$

Where:

VS (mL) = soil wet weight (g) – soil dry weight (g) + extractant volume (mL) and is the total volume of solution in the extracted soil

$MS(g) = \frac{SoilWetWeight(g) \times 100}{(100 + WS(\%))}$ and is the oven-dry equivalent of the soil sample taken for microbial biomass measurements

WS (Water Content, %) = as calculated in Equation 5

Microbial biomass C and N in the soil:

$$MB - C(\mu g \cdot g^{-1} soil) = \frac{(OC_F - OC_{UF})}{k_{EC}} \qquad \text{Equation 11}$$

$$MB - N(\mu g \cdot g^{-1} soil) = \frac{(ON_F - ON_{UF})}{k_{EN}} \qquad \text{Equation 12}$$

k_{EC} and k_{EN} represent the efficiency of extraction of microbial biomass C and N, respectively, and are 0.25 and 0.18, respectively (Voroney et al. 1993).

3.2.7. Statistical analysis

Data was analyzed using the Statistical Analysis Software (SAS Institute 1999). The experiment is a Randomized Complete Block Design with Repeated Measures. The data was analyzed according to the following model using the *Proc Mixed* procedure with the *Repeated* option:

$$Y_{ijk} = \mu + B_i + T_j + \varepsilon_{ij} + D_k + TD_{ik} + \varepsilon_{ijk}$$

Where:

Y_{ijk} = soil respiration (R_s)

μ = overall mean

B_i = the ith block (1,2,3) (random factor)

T_j = the *j*th treatment (Walker poplar, barley) (fixed factor)

ε_{ij} = error main associated with the treatment * block interaction

D_k = the *k*th date (8 & 23 June, 7 & 19 July, 9 & 22 August) (fixed factor)

TD = the interaction of treatment * date

ε_{ijk} = random error associated with the date * block + date * block * treatment interactions

The treatment factor is fixed because the treatments were not randomly selected, indicating that results from this experiment can only be applied to the research plots studied, and that they cannot be used to make wider inferences to the greater population of possible plots and treatments . Statistical differences between treatments for soil moisture, soil temperature, DOC, DON and soil respiration were tested with Tukey's Studentized Range Test using $\alpha = 0.05$. The assumption of normality was assessed using the SAS software version 9.1 *Proc UNIVARIATE* function with a Kolmogorov-Smirnov test for normality (data not shown). All data conformed to a normal distribution. A test for homogenous variance between treatments indicated a heterogeneous variance between the Walker poplar and barley residuals for soil respiration (Fig. 3.6). The model was run again by treatment to assess the effect of this difference between the two treatments; however the model was not improved, therefore the homogeneous model was used.

3.3. Results

3.3.1. Soil temperature and volumetric water content

Soil temperature at 10 cm below the mineral soil surface did not show any difference between the two crop treatments. In both the barley and Walker poplar plots, soil temperature was not statistically different before or after the treatments were applied, even though the treatments were applied 1 month apart. The soils were frozen from 1 January 2005 to the beginning of April 2005, at which point spring thaw began (Fig. 3.7a). Soil temperature rose gradually from this date until reaching a maximum in late July. Soil temperature then decreased steadily through the fall. Soil temperature closely followed the seasonal trend of air temperature at the site (data not shown). Soil volumetric water content did not differ significantly between the two treatments during the sampling period (Fig. 3.7b). The mean soil moisture content from 1 January 2005 to 20 October 2005 was 30.7 ± 2.2% in the barley treatment and 31.2 ± 1.8% in the Walker poplar treatment. Moisture content responded quickly to precipitation events and a dramatic increase in water content was seen in early April which was concurrent with the spring thaw (soil and snow).

3.3.2. Soil respiration

Soil respiration did not differ significantly between the two treatments ($p = 0.715$), however there were significant differences between sampling dates ($p = 0.001$) (Fig. 3.8). The mean respiration rate over the sampling period was 1.83 ± 0.12 µmol CO_2 m^{-2} s^{-1} (mean ± 1 standard error) and 1.89 ± 0.15 µmol CO_2 m^{-2} s^{-1} in the barley and Walker poplar plots, respectively. Both the barley and Walker poplar plots followed a similar decreasing trend from 8 June to 7 July 2005, at which point the Walker poplar efflux rate was at a minimum (1.3 ± 0.10 μmol CO_2 m^{-2} s^{-1}). After this date, the barley efflux rate continued to decrease to reach its lowest efflux rate of 1.3 ± 0.22 μmol CO_2 m^{-2} s^{-1} on the 19 July, while the Walker poplar efflux rate increased steadily until the 9 August measurement where the efflux rate was at a maximum of 2.8 ± 0.47 μmol CO_2 m^{-2} s^{-1}.

Soil respiration was not significantly affected by soil temperature (barley $p = 0.310$, Walker $p = 0.464$) or by soil moisture content (barley $p = 0.074$, Walker $p = 0.351$) in either of the two treatments. However, soil respiration did decrease with increasing moisture content in the barley treatment and soil moisture content explained 59% of the variation in soil respiration, although the relationship was not statistically significant as mentioned above.

Using the mean soil efflux values (barley = 1.83 μmol CO_2 m^{-2} s^{-1} and Walker = 1.89 μmol CO_2 m^{-2} s^{-1}), and assuming a constant respiration rate for the period from 1 May to 30 September 2005, we estimate a loss of 2.9 t C ha^{-1} in the barley plots and a loss of 3.0 t C ha^{-1} in the Walker poplar plots.

3.3.3. Net primary productivity

Net primary productivity in the barley plots was 3760.7 ± 263.80 kg ha^{-1} (dry weight), or 1639.6 ± 115.02 kg C ha^{-1}. The Walker poplar mean tree height and RCD were 378 ± 15 mm and 4 ± 0.1 mm, respectively, at time of planting. Mean tree height and RCD at the end of the growing season were 541 ± 36 mm and 6 ± 0.4 mm, respectively. Net primary productivity in the Walker poplar plots was 1.98 kg ha^{-1} (dry weight), or 0.99 kg C ha^{-1}.

3.3.4. Dissolved organic C and N and DOC:DON Ratio

Depth was not a significant factor in affecting dissolved organic C (DOC) in all plots studied ($p = 0.856$); furthermore, there was no treatment effect ($p = 0.296$). The barley plots DOC means were 328.1 ± 127.19, 368.6 ± 176.60 and 348.3 ± 151.76 μg g^{-1} soil for the 0-10, 10-20 and 0-20 cm sampling intervals, respectively (Fig. 3.9a). DOC averaged only 229.5 ± 43.01, 229.2 ± 48.55 and 229.3 ± 45.75 μg g^{-1} soil for the 0-10, 10-20 and 0-20 cm intervals in the Walker poplar plots.

Similarly to the DOC, DON did not differ between the two treatments ($p = 0.945$) nor did it differ between the different depth intervals ($p = 0.503$, Fig 3.9b). The treatment means were almost identical for all three depth intervals considered: 54.8 ± 23.25 and 53.5 ± 9.75 μg g^{-1} soil for the barley and Walker poplar plots respectively, for the 0-10 cm interval; 43.6 ± 20.53 and 42.6 ± 8.19 μg g^{-1} soil for the barley and Walker poplar plots respectively, for the 10-20 cm interval; and 49.2 ± 21.82 and 48.0 ± 8.76 μg g^{-1} soil for the barley and Walker poplar plots respectively, for the 0-20 cm interval.

Treatment ($p < 0.0001$) and depth ($p = 0.0012$) were both significant factors in affecting the DOC:DON ratio (Fig. 3.9c). Treatment means in the barley treatment were 6.3 ± 0.39, 8.3 ± 0.39 and 7.1 ± 0.08 for the 0-10, 10-20 and 0-20 cm intervals, respectively. Walker poplar treatment means were much smaller: 4.3 ± 0.11, 5.4 ± 0.28 and 4.7 ± 0.08 in the 0-

10, 10-20 and 0-20 cm intervals, respectively. The mean DOC:DON across both treatments for the 0-10 and 10-20 cm interval were 5.3 ± 0.48 and 6.9 ± 0.70, respectively.

3.3.5. Microbial biomass C and N (MB-C and MB-N)

The effects of treatment ($p = 0.299$) and soil depth ($p = 0.261$) were not significant in determining MB-C (Fig. 3.10a). The barley tended to have higher amounts of MB-C than the Walker poplar plots but the differences were not significant. The barley MB-C means were 1709.9 ± 904.19, 1374.6 ± 865.48 and 1542.2 ± 881.07 $\mu g\ g^{-1}$ soil in the 0-10, 10-20 and 0-20 cm sampling intervals, respectively. MB-C in the 0-10, 10-20 and 0-20 cm intervals was 1105.5 ± 313.05, 839.7 ± 250.06 and 972.6 ± 278.73 in the Walker poplar plots, respectively.

As was the case for MB-C, MB-N was not significantly affected by treatment ($p = 0.328$) nor by sampling depth ($p = 0.298$). In the three sampling depths (0-10, 10-20 and 0-20 cm), MB-N in the barley plots was slightly greater than in the hybrid poplar plots, although the differences were not statistically significant (Fig 3.10b).

3.4. Discussion

Intuitively, soil temperature in the barley plots was anticipated to have been lower than in the hybrid poplar plots because the hybrid poplar plots have more exposed mineral soil as compared to the barley soil which has more shading from the dense crop, however this was not the case. Our data shows no difference in terms of soil temperature between the two land-uses in the first year after land-use conversion. Soil temperature is tightly coupled with soil respiration rates; efflux is commonly expressed as an exponential function of soil temperature or with Arrhenius equations (Fang and Moncrieff 2001), and the Q_{10}, that is the dependence of soil respiration on temperature, and is derived from such equations. Grigal and Berguson (1998) suggest that a lack of shade provided by vegetation for a large portion of the year and the absence of detritus at the soil surface tend to increase soil temperatures in row-crop systems as compared to plantations, which would thus increase oxidation of C. This conclusion is also supported by Bouwman and Leemans (1995) who reported that higher soil temperature and moisture content lead to higher rates of decomposition in arable soils. One must argue that during the early stages of plantation development, before the trees are able to produce much foliage to cover the soil surface and prior to canopy closure, the soil surface in a plantation would be exposed to solar radiation as much as the row-crop agricultural system, or even more exposed (assuming plantation management to control weeds and pioneer species). The soil surface remains bare (exposed mineral soil) through cultivation for a number of years after plantation establishment, which may actually render the site more vulnerable to soil warming during the warmest times of the year while the row-crop system provides some shading for the soil. Vesterdal et al. (2002) revealed a possible lag time of 10 years before the formation of a forest floor after the transition from agriculture to forestry. The conclusions of the previously mentioned studies are valid when discussing established plantations but are not suitable for the plantation establishment period. This establishment period is crucial in terms of the C balance of the plantation, as the younger plantations are likely larger sources of C to the atmosphere than more mature plantations.

I hypothesized that soil respiration rates would be greater in the barley plots than in the hybrid poplar plots. Respiration rates were not different between the two treatments in the first year after land-use conversion and thus the hypothesis has to be rejected for the studied period. This may be explained by similar soil temperatures and soil moisture contents throughout the entire sampling period, leading to similar respiration rates, as soil temperature and moisture content have been shown to have a strong influence on soil respiration. Furthermore, respiration rates in the barley and Walker plots are declining as soil water content and temperature are increasing. Respiration rates usually increase with increasing temperature, however if water content is too high, it may limit oxygen supply to microorganisms, hence decreasing soil respiration. The effect of excessive soil moisture may be overriding the effect of soil temperature on soil respiration in the plots, which is usually tightly linked to respiration rates. Other than soil temperature and moisture content, there are numerous other factors that may affect soil respiration rates, one of which is previous land-use. Soil respiration is driven by C inputs into the soil. The plantations and barley plots in this study were historically managed as one unit, and therefore have had the same inputs for many years. Furthermore, the year prior to land conversion (2004), all plots were seeded to barley. This suggests that the respiration in the first year after land-use conversion was fueled by the residual materials that were ploughed into the soil prior to planting and seeding in 2005. This conclusion is supported by Grigal and Berguson (1998) who found that soil C loss during the first year of plantation was equal to the loss under the previous land-use. They also concluded that soil C loss would gradually decline to 75% the loss in year one within five years due to mulching, shading and lack of soil disruption. I suggest the rates of soil respiration or soil C loss may decrease at a faster rate for other reasons. The primary reason for a fast decrease in soil respiration would be the lack of C inputs into the soil of the plantation. DOC is the form of C that is readily available for microbial decomposition and eventually oxidation. Annual deposits of organic material (leaves, twigs, branches at the soil surface) and constant fine root production and turnover, coarse root decay, release of root exudates and rhizodeposition beneath the soil surface are important sources of substrates for soil organisms (Randerson et al. 1996), including microbial populations. When land is converted from agricultural use to plantation forestry, these pathways are almost completely removed for the first few years of plantation growth, especially in boreal regions of the northern hemisphere where the growing season can be quite brief. Furthermore, autotrophic respiration from the tree root systems is very small as compared to heterotrophic processes. The results showed that the pool of DOC was lower in the Walker poplar plantations being only 66% as compared to the barley plots in the 0-20 cm depth interval. I argue that a continued decrease of the DOC in the Walker poplar plots and possible large depletion as a result of insignificant inputs could drastically reduce respiration rates. If the soil organisms continue to consume the DOC at a faster rate than the input from organic detritus, this pool may be depleted faster than it can be replenished under local conditions. Post and Kwon (2000) noted that two sites under study showed large losses of soil organic carbon (SOC) due to a lack of inputs in the early stages of forest growth. This could lead to a reduction in microbial activity due to substrate limitations and trigger a decrease in CO_2 efflux. The true effect of land-use conversion on soil respiration will not be evident until the soil responds to the new C input regime and reaches a new equilibrium (Guo and Gifford 2002).

A chemically labile portion of soil organic matter, termed respiratory substrate, is easily used by microorganisms and is considered to have a direct impact on soil respiration (Liu et al. 2006). Wang et al. (2003) reported that water soluble C is regarded as an indicator of the most immediate organic substrate for microorganisms; this is the same as DOC in the current study. The similarity in the respiration rates between the two land-uses may be explained by considering the differences in soil DOC:DON ratio and microbial biomass between the barley and Walker poplar treatments. The DOC:DON ratio can be used as an indicator of the relative speed of decomposition; Taylor et al. (1989) found the C:N ratio of substrate to be the best predictor of mass loss and decay. In the current study, the DOC:DON ratio is smaller in the Walker plots. This is most certainly a result of the difference in residue inputs between the two treatments. The Walker plots receive very little inputs of fresh organic residues as opposed to the barley plots, which have higher input rates from sloughing materials and root turnover (implied by higher NPP). The older organic residues in the Walker plots have had longer to decompose and therefore the C:N ratio is smaller, and the opposite is true for the fresh barley residues; this is consistent with the findings of Schlesinger (1985) who showed that litter decay resulted in a decline in the C:N ratio. Parmelee et al. (1989) reported that Johnson grass (*Sorghum halepense* (L.)) residues had the highest C:N ratio and slowest decay rate as compared to sicklepod (*Cassia obtusifolia* (L.)) and pigweed (*Amaranthus retroflexus* (L.)), which both had a lower C:N ratio and exhibited rapid decay. From this we can estimate that residue decay, and therefore respiration rates, should be lower in the barley plots because the DOC:DON ratio is larger than in the Walker poplar treatment. The second element to consider is the size of the microbial biomass pools. The microbial biomass C and N is much higher in the barley treatments (Fig.3.9). This indicates a larger microorganism population in the soil beneath the barley crop, which would also imply higher respiration rates in this land-use. The higher respiration rates suggested by the larger pool of microbial biomass in the barley may be offset by the reduced efficiency in consumption of the organic residues due to a higher C:N ratio of the substrates. This may not be true in all cases, as Wang et al. (2003) reported that soil respiration was regulated more by substrate supply than by the size of the microbial biomass pool under ideal soil temperature and moisture (also see Jenkinson and Powlson 1976; Jenkinson et al. 1976).

Net ecosystem productivity is the difference between photosynthesis and respiration (Trumbore 2002). Most studies have found that agricultural land, newly converted to plantation trees, has a higher total respiration rate (loss of C to the atmosphere) than the photosynthetic rate (C assimilated from the atmosphere) of the crop plants, making it a net source of C to the atmosphere. Vesterdal et al. (2002) proposed the decline in C stores in the soil may be a result of low inputs of C from young stands that are outweighed by decomposition of soil C remaining from agricultural practices. Hansen (1993) hypothesized that C loss was a result of rapid decomposition during the first several years of plantation establishment, but that these losses may eventually be compensated for in the latter years of the rotation (after 6-12 years). Bashkin and Binkley (1998), with the use of C isotopes, were able to conclude that the effect of afforestation on soil C was dependent on new C gains and on C lost from the previous management. In the present study, NEP can be estimated as the difference between NPP and soil respiration during the growing season. This estimation is not used as a concrete value for NEP in the two land-uses studied, however such an estimation illustrates an important concept when discussing land-use conversion. In both land-uses, the respiration rates were the same. Therefore the difference in NEP is a result of differences in NPP between the two treatments in the first year after land-use conversion. This hypothesis is supported by the numerous studies discussed above which conclude that soil respiration rates are reliant on soil temperature and previous land-use. In the current study, both systems are net sources of C to the atmosphere. The barley is a much smaller source, with a net loss of approximately 1.3 t C ha^{-1} yr^{-1} to the atmosphere, while the Walker poplar plantation has an estimated net loss of 3.0 t C ha^{-1} yr^{-1}, making it a much larger source of C to the atmosphere during the first year after land-use conversion.

3.5. Conclusions

Soil respiration rates were the same in both the barley crop and hybrid poplar plantation land-uses. Although differences in DOC, DON, MB-C and MB-N were found between the treatments, these variables did not seem to be of major importance at this early stage of land conversion in controlling soil respiration. The dominant factors that govern soil respiration such as soil temperature, soil moisture, and inputs of organic materials from the previous land-use, which, in this case, was a barley crop in 2004 on all research plots, were similar in both land-uses. Due to similar soil temperatures, moistures, and organic inputs, soil respiration remained the same in both treatments over the sampling period. Despite these assertions, a strong relationship between soil temperature and respiration was not found in this study, assumed to be the result of low variation in soil temperature between the sampling dates; however, a weak relationship between soil moisture content and soil respiration in the barley plots was observed. Lower amounts of DOC in the Walker poplar plots suggests the start of a transition in the C pools due to the change in land-use, however the effect of this change on soil respiration was not apparent during the sampling period. The effect of the decrease in DOC will likely be manifested in later years. The most important factor to consider that may determine the C source or sink status of the site is the NEP of the two land-uses. Due to almost identical soil respiration rates, the greater NPP in the barley plots determines that NEP was greater in the barley treatment in the first year after land conversion.

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Table 3.1. Soil profile description for each research site recorded in October 2005.

Horizon	Depth (cm)	Description
Plot 1, Walker Poplar, Orthic Humic Gleysol		
Ap	0-23	Very dark brown (10YR 2/2 d); silt loam; weak, fine granular; abundant, fine, random, inped and exped roots; abrupt, smooth boundary; 23-25 cm thick.
Ah	23-45	Very dark grayish brown (10YR 3/2 d); silt loam; weak, fine granular; few, fine, exped roots; gradual, wavy boundary; 22-30 cm thick.
Bg	45-95	Light brownish gray (10YR 6/2 d); clay loam; amorphous; few, fine, faint mottles; few, fine, exped roots; abrupt, smooth boundary; 50-53 cm thick.
Ccag	95-130	Light gray (10YR 7/2 d); silty clay loam; amorphous; common, fine, distinct mottles; abrupt, smooth boundary; 35-38 cm thick.
IICkg	130+	Very pale brown (10YR 7/3 d); loamy sand; single grain; common, fine, distinct mottles.
Plot 2, Barley, Orthic Humic Gleysol		
Ap	0-25	Very dark brown (10YR 2/2 d); silt loam; weak, fine granular; friable; abundant, fine, random inped and exped roots; abrupt, smooth boundary; 25-28 cm thick.
Ah	25-36	Dark gray (10YR 4/1 d); silt loam; weak, fine platy; very friable; abundant, fine, oblique, exped roots; abrupt, smooth boundary; 11-13 cm thick.
Bg	36-54	Grayish brown (10YR 5/2 d); loam; amorphous; many, medium to coarse, prominent mottles; plentiful, fine, vertical roots; abrupt, smooth boundary; 18-20 cm thick.
ICg	54-120	Gray (10YR 5/1 d); silty clay loam; amorphous; many, fine, prominent mottles; abrupt, smooth boundary; 66-70 cm thick.
IICg	120-130	Light yellowish brown (10YR 6/4 d); sand; single grain; abrupt, smooth boundary; 10-12 cm thick.
IIICg	130+	Light brownish gray (10YR 6/2 d); silty clay loam; amorphous; many, fine to medium, prominent mottles.

Plot 3, Walker Poplar, Orthic Humic Gleysol		
Ap	0-24	Very dark brown (10YR 2/2 d); silt loam; weak, fine granular; plentiful, fine, random, inped roots; abrupt, smooth boundary; 24-26 cm thick.
Bg	24-42	Gray (10YR 5/1 d); loam; amorphous; many, medium to coarse, prominent mottles; plentiful, random, fine, exped roots; abrupt, smooth boundary; 18-20 cm thick.
ICg	42-115	Gray (10YR 6/1 d); clay loam; amorphous; many, fine to medium, prominent mottles; few, fine, random, exped roots; abrupt, smooth boundary; 73-76 cm thick.
IICg	115-125	Light yellowish brown; (10YR 6/4 d); sand; single grain; few, coarse, prominent mottles; abrupt, smooth boundary; 10-12 cm thick.
IIICg	125+	Light yellowish brown (10YR 6/2 d); silty clay; amorphous; many, fine to medium, distinct mottles.
Plot 4, Barley, Orthic Humic Gleysol		
Ap	0-21	Very dark brown (10YR 2/2 d); silt loam; weak, fine granular; abundant, fine, random, inped roots; abrupt, smooth boundary; 21-24 cm thick.
Ahe	21-32	Light brownish gray (10YR 6/2 d); silt loam; weak, fine platy; few, fine, random, exped roots; abrupt, smooth boundary; 11-13 cm thick.
Bg	32-39	Pale brown (10YR 6/3 d); silt loam; weak, fine platy; many, fine to medium, prominent mottles; few, fine, random, exped roots; abrupt, smooth boundary; 7-9 cm thick.
ICg	39+	Gray (10YR 6/1 d); silty clay loam; amorphous; many, fine to medium, prominent mottles; few, fine, horizontal, exped roots.
Plot 5, Walker, Orthic Humic Gleysol		
Ap	0-22	Very dark gray (10YR 3/1 d); silt loam; weak, fine granular; abundant, random, fine, inped and exped roots; abrupt, smooth boundary; 22-24 cm thick.
Ahe	22-31	Dark gray (10YR 4/1 d); silt loam; weak, coarse platy; abundant, fine, random, inped and exped roots; abrupt, smooth boundary; 9-11 cm thick.
Bg	31-36	Grayish brown (10YR 5/2 d); silt loam; amorphous; common, medium to coarse, prominent mottles; few, fine, random, exped roots; abrupt, smooth boundary; 5-8 cm thick.
ICg	36+	Gray (10YR 5/1 d); silty clay loam; amorphous; many, fine to medium, prominent mottles; few, fine, horizontal roots.

Plot 6, Barley, Humic Luvic Gleysol

Ap	0-21	Dark gray (10YR 4/1 d); silt loam; weak, fine granular; abundant, fine, random, inped and exped roots; abrupt, smooth boundary; 21-24 cm thick.
Ahej	21-27	Grayish brown (10YR 5/2 d); loam; weak, coarse platy; abundant, fine, random, exped roots; abrupt, smooth boundary; 6-9 cm thick.
Aeg	27-39	Brown (10YR 5/3 d); silt loam; weak, fine platy; many, medium to coarse, prominent mottles; plentiful, fine, oblique, exped roots; abrupt, smooth boundary; 12-14 cm thick.
Btg	39+	Gray (10YR 5/1 d); silty clay loam; fine, subangular blocky; many, fine to medium prominent mottles; few fine, oblique, exped roots.

Table 3.2. Soil characteristics (Horizon- Classified according to the Canadian System of Soil Classification, TOC- Total Organic C, TON- Total Organic N, pH_{H2O} – soil pH in water, pH_{CaCl2} – soil pH in calcium chloride, %clay, silt, sand – textural analysis).

Horizon	Depth (cm)	TOC (%)	TON (%)	pH H_2O	pH $CaCl_2$	% clay	% silt	% sand
Plot 1, Walker Poplar, Orthic Humic Gleysol								
Ap	0-23	16.25	0.85	7.40	6.88	21.48	39.01	39.51
Ah	23-45	2.25	0.23	7.11	6.56	27.19	47.96	24.85
Bg	45-95	0.77	0.01	7.71	7.16	34.50	43.50	22.00
ICcag	95-130	0.50	0.05	8.00	7.30	29.70	50.60	19.70
IICkg	130+	0.16	0.02	8.21	7.10	2.70	21.60	75.70
Plot 2, Barley, Orthic Humic Gleysol								
Ap	0-25	16.22	0.94	7.80	6.89	16.00	38.79	45.21
Ah	25-36	1.37	0.08	6.44	6.49	14.74	45.42	39.84
Bg	36-54	1.01	0.07	7.07	6.23	19.60	47.70	32.70
ICg	54-120	0.70	0.08	6.46	5.64	34.70	46.30	19.00
IICg	120-130	0.21	0.02	6.63	5.70	2.40	6.10	91.50
IIICg	130+	0.46	0.07	6.95	6.07	39.20	46.40	14.40
Plot 3, Walker Poplar, Orthic Humic Gleysol								
Ap	0-24	9.11	0.60	6.93	6.65	18.70	44.45	36.84
Bg	24-42	0.66	0.05	6.36	6.19	18.00	46.40	35.60
ICg	42-115	0.56	0.06	5.86	5.55	37.00	41.90	21.10
IICg	115-125	0.12	0.02	5.87	5.67	4.00	7.20	88.70
IIICg	125+	0.58	0.07	6.28	5.97	42.80	55.30	1.90
Plot 4, Barley, Orthic Humic Gleysol								
Ap	0-21	9.44	0.49	7.08	6.92	14.21	46.42	39.38
Ahe	21-32	0.61	0.03	6.76	6.63	11.50	47.80	40.70
Bg	32-39	0.90	0.06	7.23	6.80	17.70	51.80	30.50
ICg	39+	0.64	0.07	6.59	6.18	37.40	45.70	16.90
Plot 5, Walker, Orthic Humic Gleysol								
Ap	0-22	9.11	0.50	6.98	6.38	14.44	44.94	40.63
Ahe	22-31	1.66	0.12	5.96	5.26	15.70	49.86	34.44
Bg	31-36	0.57	0.04	5.98	5.18	18.20	51.20	30.60
ICg	36+	0.69	0.08	6.43	5.51	38.90	43.20	17.90
Plot 6, Barley, Humic Luvic Gleysol								
Ap	0-21	2.98	0.18	6.06	6.57	15.84	50.67	33.49
Ahej	21-27	2.16	0.12	6.09	4.96	15.60	44.70	39.80
Aeg	27-39	0.49	0.04	6.02	5.25	18.20	48.70	33.20
Btg	39+	0.73	0.06	6.10	5.49	39.10	47.70	13.20

Figure 3.1. Location of the research site.

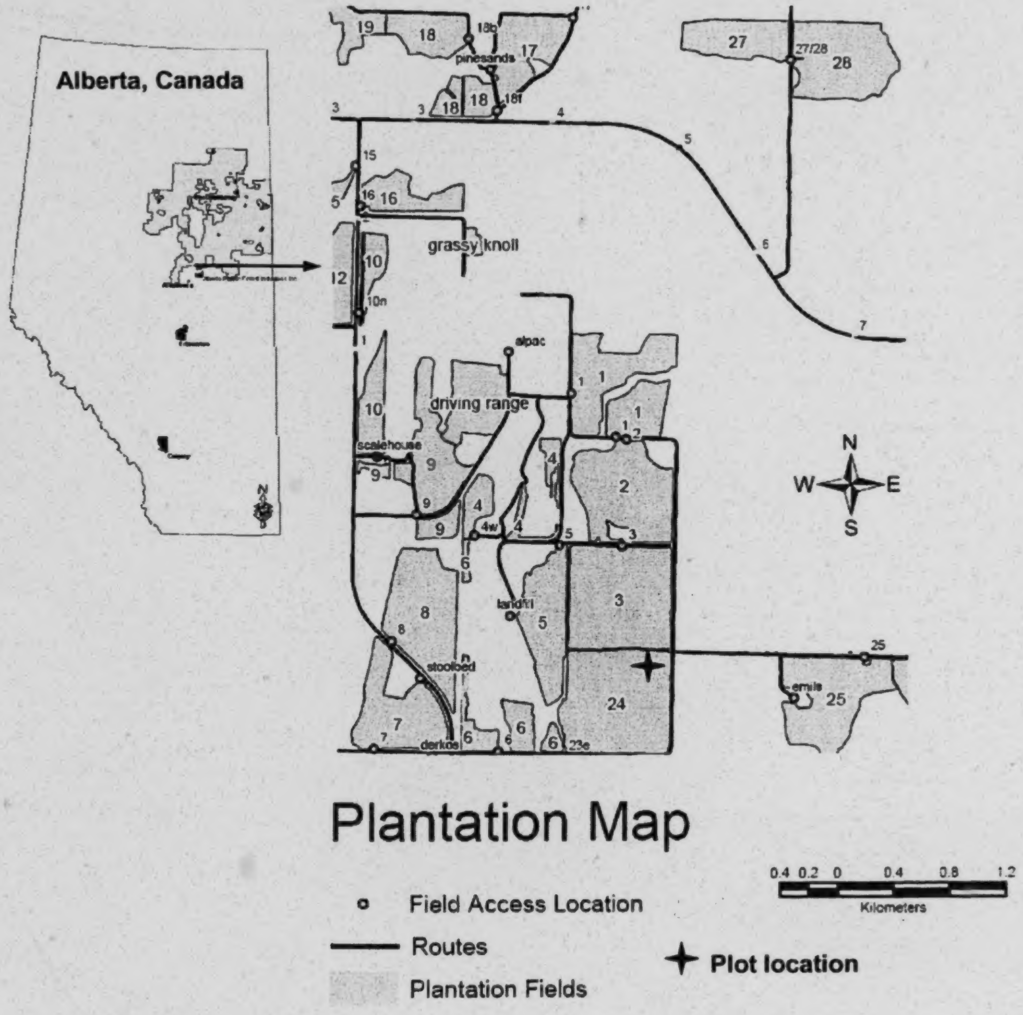

Alberta, Canada
19
18
18b
17
pinesands
27
27/28
28
3
18
18
18f
4
5
15
16
16
grassy knoll
12
10
10n
alpac
1
1
1
driving range
10
scalehouse
9
9
9
4
4w
4
2
5
3
6
8
8
landfill
5
3
stoolbed
24
25
emile
25
7
7
derkos
6
6
6
23e
7
6
N
W
E
S
Plantation Map
0.4 0.2 0 0.4 0.8 1.2
Kilometers
Field Access Location
Routes
Plantation Fields
Plot location

Figure 3.2. Plot layout of the land-use conversion experiment.

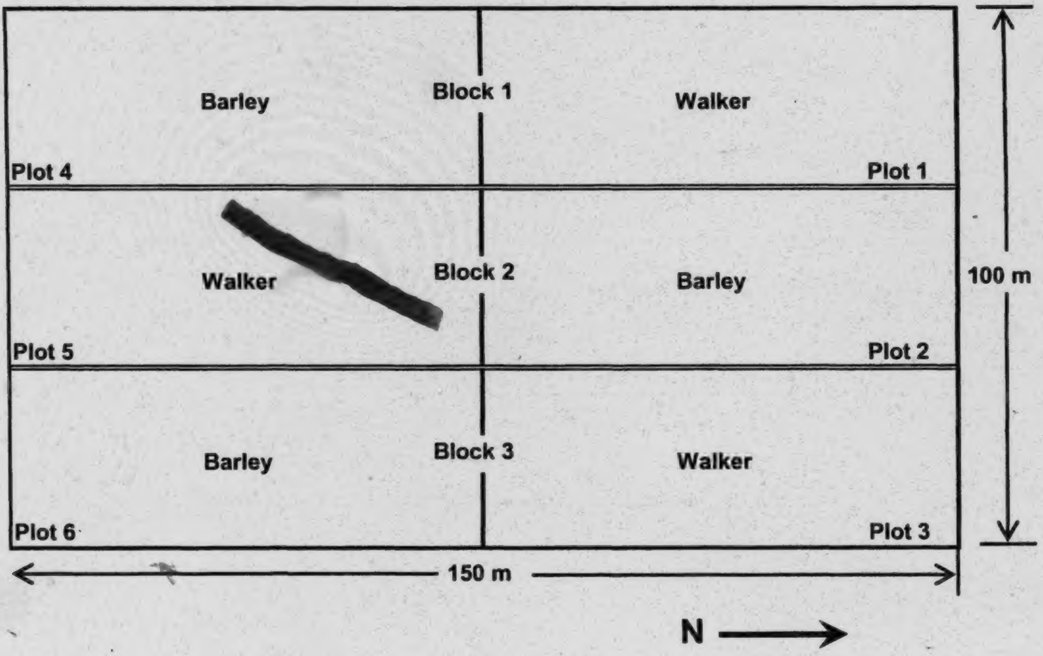
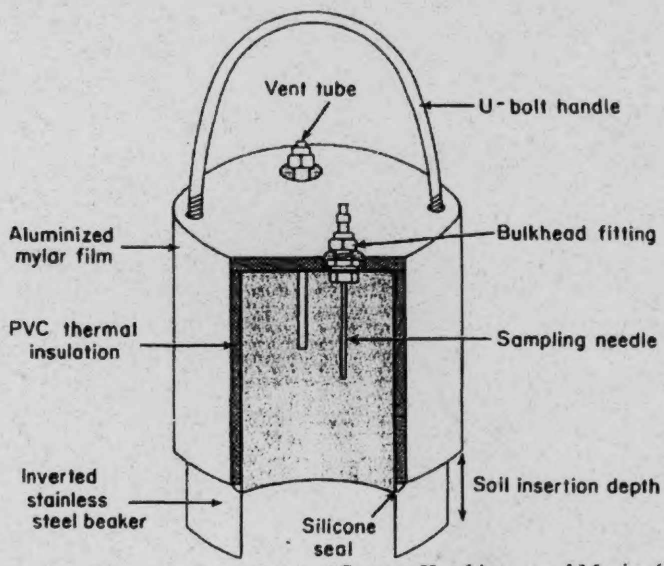

Barley
Block 1
Walker
Plot 4
Plot 1
Walker
Block 2
Barley
Plot 5
Plot 2
Barley
Block 3
Walker
Plot 6
Plot 3
100 m
150 m
N

Figure 3.3. Schematic diagram of the Hutchinson static gas chamber.


Vent tube
U-bolt handle
Aluminized mylar film
Bulkhead fitting
PVC thermal insulation
Sampling needle
Inverted stainless steel beaker
Soil insertion depth
Silicone seal

Source: Hutchinson and Mosier (1981)

Figure 3.4. Sample calibration curve for the Varian CP-3800 Thermal Conductivity Detector.

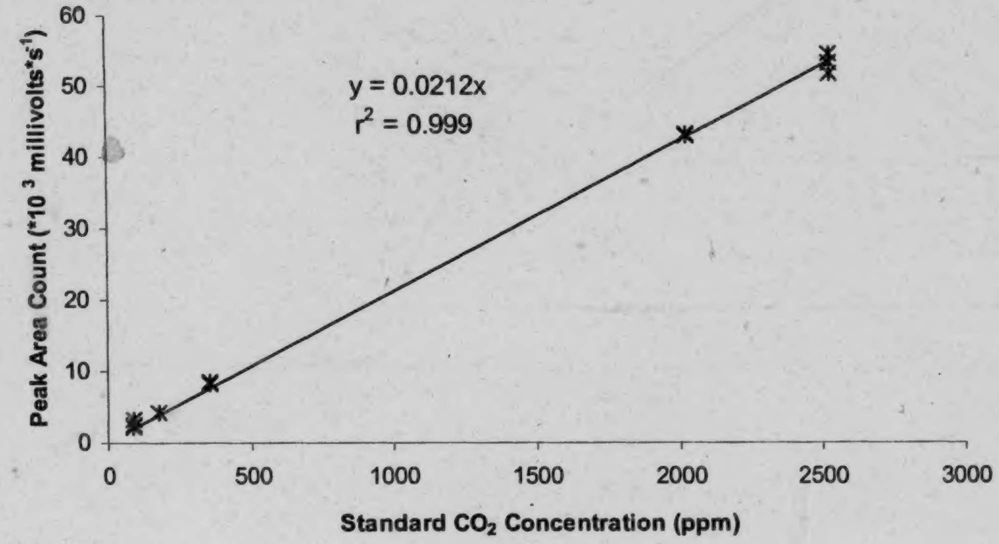


Figure 3.5. Two samples depicting the non-linearity of CO_2 increase in the Hutchinson static gas chambers sampled from the newly established hybrid poplar plantation on 19 July 2005.

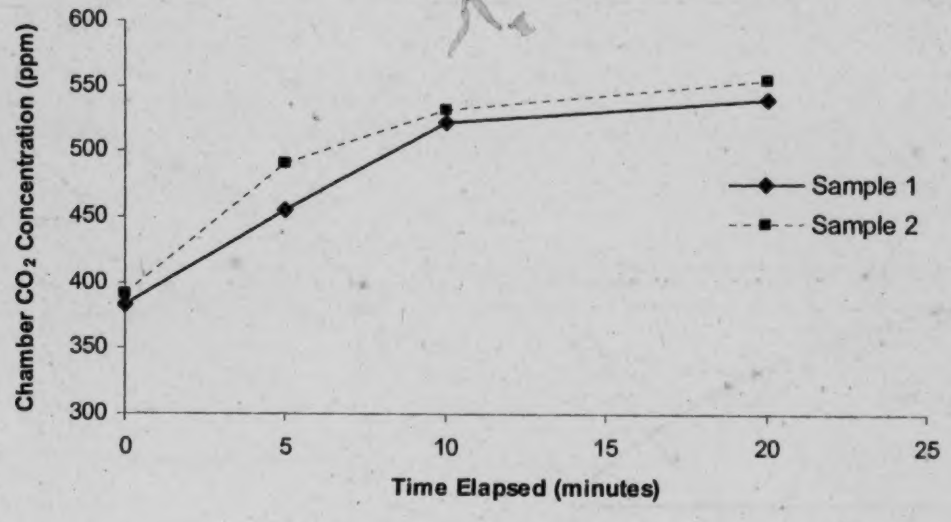


Figure 3.6. Box-plot of residuals values of soil respiration plotted by treatment.

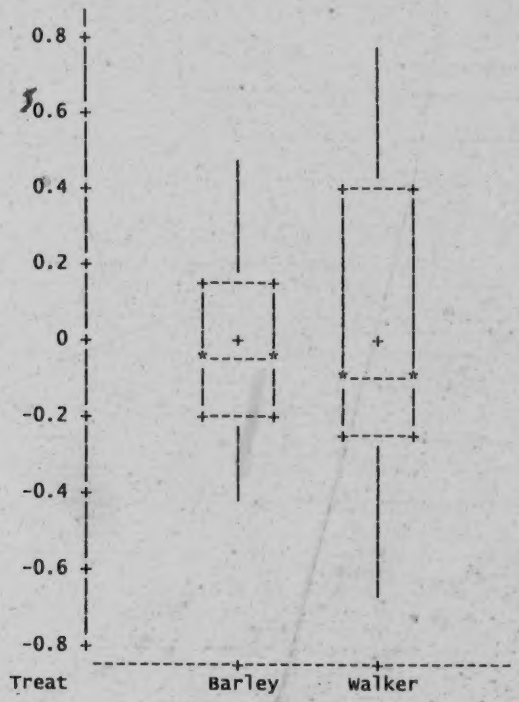


Figure 3.7. Seasonal trend of a) soil temperature at 10 cm and b) soil volumetric water content at 10 cm (line) and precipitation (bar) in the barley and Walker poplar plots from 1 January to 23 November 2005.

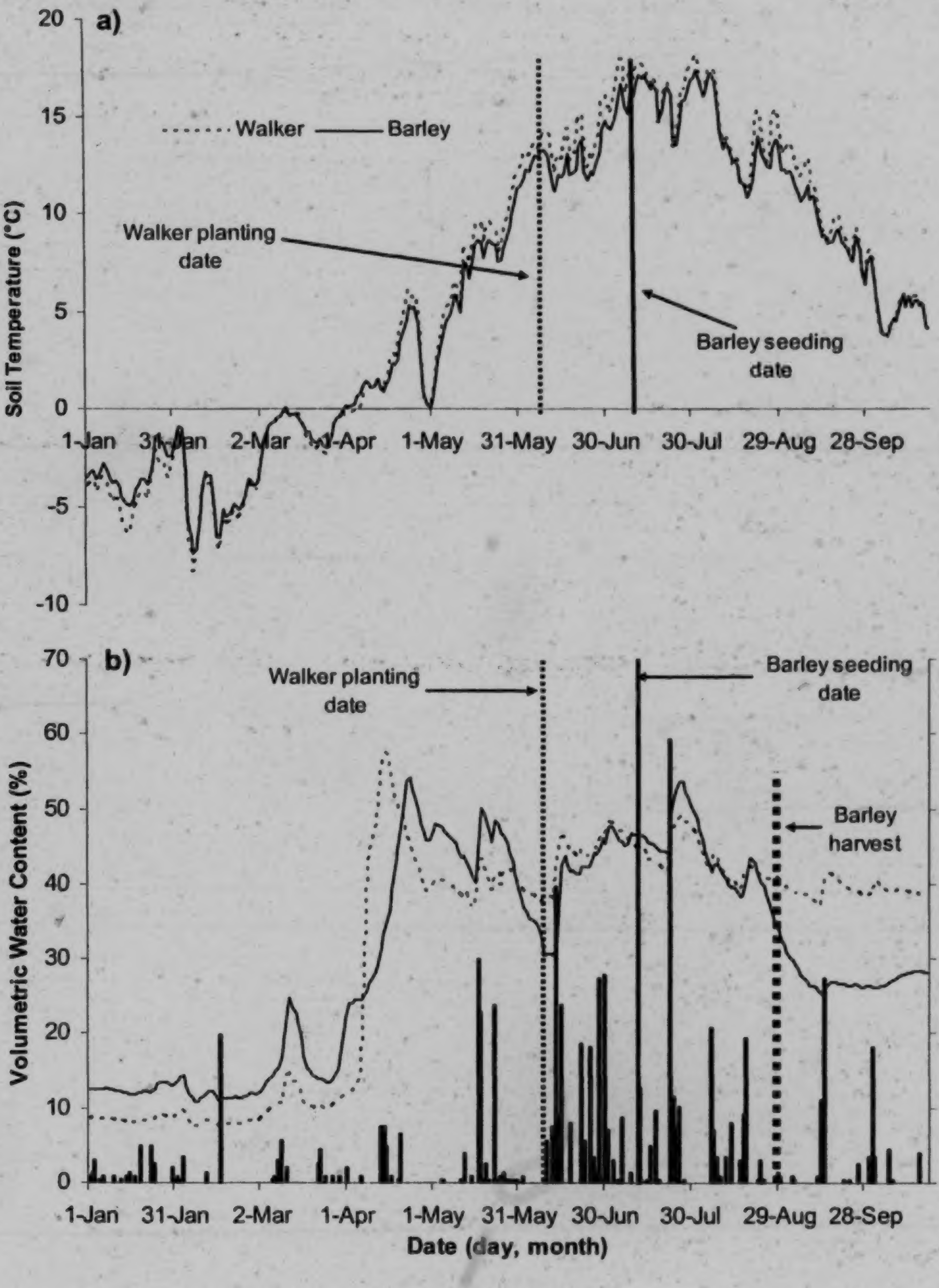


Figure 3.8. Mean soil efflux (± s.e.) rates in summer 2005 in barley and Walker poplar plots. Different upper case letters indicate statistical differences between the sampling dates for barley plots; different lowercase letters indicate statistical differences between the sampling dates for Walker polar plots ($\alpha = 0.05$).

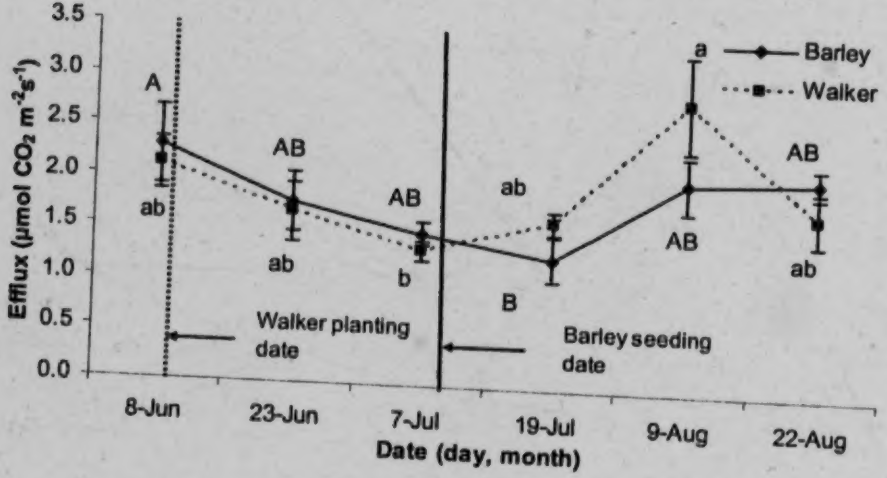


Figure 3.9. Mean values (± s.e.) of a) dissolved organic C, b) dissolved organic N and c) DOC:DON ratio in the barley and Walker poplar plots for 0-10, 10-20 and 0-20 cm mineral soils. Different uppercase letters indicate significant differences between treatments while different lowercase letters indicate significant differences between sampling depths at $\alpha = 0.05$.

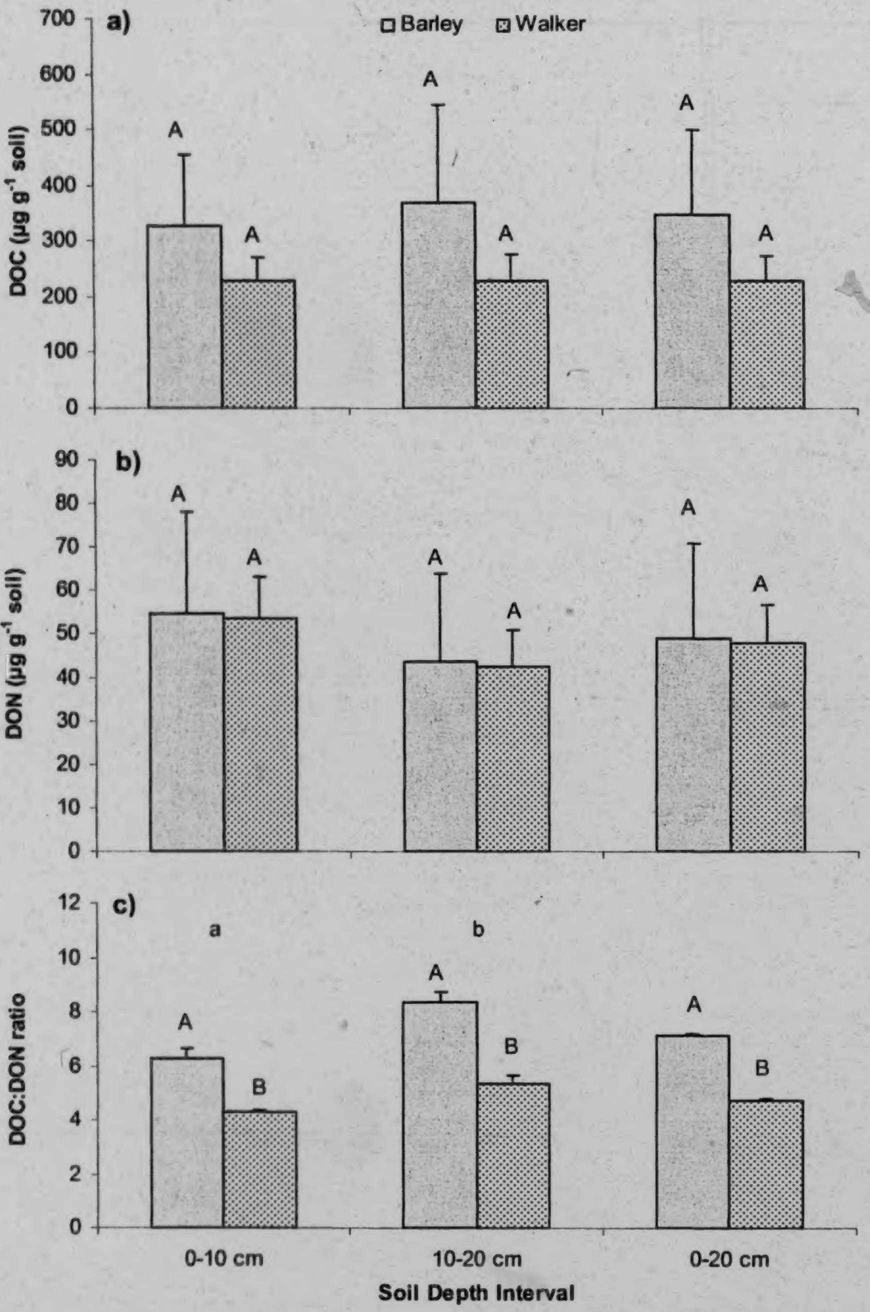
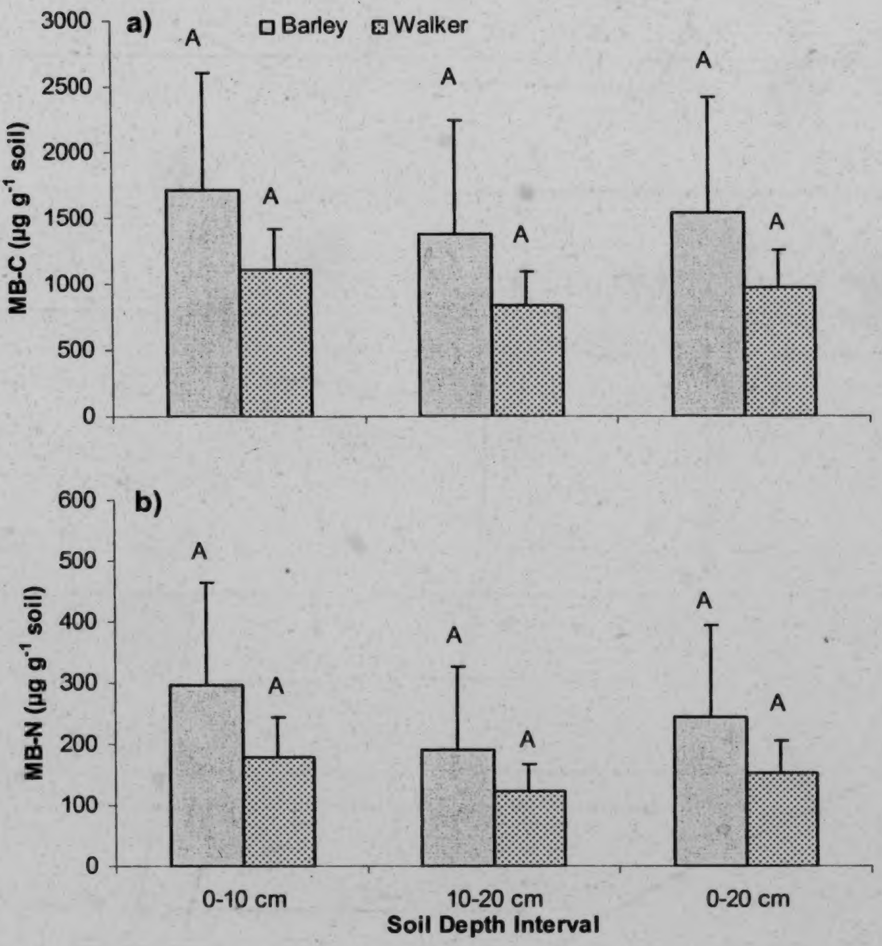


Figure 3.10. Mean values (± s.e.) of a) microbial biomass C in the barley and Walker poplar plots and b) microbial biomass N in the barley and Walker poplar plots. Different uppercase letters indicate significant differences at α = 0.05.



4. ROOT AND HETEROTROPHIC RESPIRATION RATES ACROSS A HYBRID POPLAR PLANTATION CHRONOSEQUENCE IN NORTHERN ALBERTA

4.1. Introduction

Understanding the role of the carbon (C) cycle in our natural ecosystems has become central to the study of C sequestration within the biosphere. Carbon sequestration is the long-term removal or transfer and storage of atmospheric carbon dioxide (CO_2) in the terrestrial biosphere (vegetation and soils), underground (geologic repositories), or the oceans, in a form in which the C is not quickly oxidized and/or re-emitted as CO_2 to the atmosphere (Lal et al. 2003; U.S. Department of Energy 2006). Human-induced changes to the global climate are continuously altering natural systems, and these changes were addressed internationally by the creation of the Kyoto Protocol. With the framework developed for the Kyoto Protocol, afforestation is an eligible forest carbon management activity that can be used to offset net national emissions of carbon dioxide and has the potential to increase C sequestration in the soil (Smith 1999). Planting of fast-growing hybrid poplars represent an opportunity to sequester C in the form of wood biomass aboveground, but more importantly, when planted on marginal farmland, can provide a viable method of replenishing the belowground soil C stocks through litter deposition, rhizodeposition of root exudates and root decomposition.

Soil C is a significant component of total carbon accumulation in native forests and plantations (Turner and Lambert 2000). The largest pathway in which C is lost from soil is via the release of CO_2 to the atmosphere (Raich and Mora 2005) which originates from heterotrophic and autotrophic metabolism, collectively referred to as soil respiration (Wiseman and Seiler 2004; Martin and Bolstad 2005). Numerous studies have elucidated the effects of abiotic factors such as temperature and soil moisture content on total soil respiration (R_s) rates under field conditions and in laboratory incubation experiments; however to properly analyze the efflux of CO_2 to the atmosphere and the effect that changing climate will have on net ecosystem exchange of carbon, we must separate the contributions of root respiration (R_r) and heterotrophic respiration (R_h) to R_s and interpret the effects of various biotic and abiotic factors on both sources individually (Schuur and Trumbore 2006). Hanson et al. (2000) report three methods primarily used to identify the contributions of R_r and R_h to R_s: integration of respiration components involved in soil respiration, comparison of root excluded plots to control plots, and use of stable or radioactive isotope methods. All three methods have advantages and disadvantages, the least disruptive to soil conditions being the use of isotopes (Hanson et al. 2000).

The contribution of root (autotrophic) respiration to total soil respiration has been determined in many studies; these values are likely specific to site conditions and related to local climatic and environmental conditions, tree age and species. From 49 – 57% of R_s was found to originate from R_r in a 10-yr-old Japanese cedar (*Cryptomeria japonica* D. Don) plantation using the gap analysis technique (Ohashi et al. 2000) and Lee et al. (2003) reported a contribution of R_r to R_s of 27 – 71% in a 40-yr-old temperate deciduous forest in central Japan (trenching method). Proportions of R_r were similar in a mature black spruce (*Picea mariana* (Mill.) BSP) stand in Alaska where R_r was 37 – 53% of R_s (Schuur and Trumbore 2006, isotope mass balance technique) and in a mixed Scots pine

(*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) stand in Sweden where R_r was 33 – 63% of R_s (Widen and Majdi 2001, excised root method). However Widen and Majdi (2001) also reported a steady decrease in the contribution of R_r to R_s over the growing season with values as low as 12 – 16% in October. Another study of Scots pine in northern Sweden by Hogberg et al. (2001) reported a much narrower range of 52 – 56% using the tree girdling approach. Maier and Kress (2000) found R_r to range from 50 – 73% of R_s in an 11-yr-old loblolly pine (*Pinus taeda* L.) stand (excised root method). A greenhouse study by Chen et al. (2006) found that root contributions to soil respiration ranged from 43 – 66% in young radiata pine (45 weeks old, *Pinus radiata* D. Don). A study of root respiration in the tropical forest of Brazil revealed a contribution of 24 – 35% in a clay textured soil and 35% in a sandy loam textured soil (Silver et al. 2005, trenched plot and mass balance methods). Hanson et al. (2000) reported a root contribution to soil respiration mean value of 45.8% for forest vegetation in an extensive review of literature.

The objective of this research was to determine the contribution of root respiration to total soil respiration in a chronosequence of hybrid poplar plantations using a trenched-plot method. I hypothesized that root respiration will become increasingly larger with stand age, and will also represent a higher proportion of total soil respiration as plantation age increases due to the size of the root system. The study also focuses on the effects of soil abiotic and biotic conditions and their role in controlling soil respiration across the chronosequence.

4.2. Materials and Methods

4.2.1. Site description

For a complete site description, the reader is referred to Chapter 3, Methods and Materials. The plantation stands studied in this chronosequence occurred on gleysolic, brunisolic and regosolic soils (Table 4.1, Soil Classification Working Group 1998), which is consistent with the soil survey report of the Tawatinaw Mapsheet (83-I, Kjearsgaard 1972). The plantations from this experiment are all established on previously cleared and cultivated, marginally productive land. The chronosequence contains two replications of four age-classes of hybrid poplars: 4-yr-old, 6-yr-old, 8-yr-old and 13-yr-old. All 8 plots are within an area with a radius of approximately 6 km. A lack of L, F or H horizons on all but two sites can be attributed to mechanical maintenance (disking and mowing) of the plantations and a very small amount of litterfall input in the younger stands; however the 13- and 8-yr-old sites show moderate accumulation of detritus between aligned trees within rows, but very little between rows. The study area lies in a region of complex parent material deposition because it is located within 2 km of the Athabasca River. A variety of soil series are intimately intertwined within the research area. The 13-yr-old plantations are both found on the Codesa Complex overlying the Tolman series. These soil complexes are characterized by sandy loam to loamy sand textures of alluvial material over loamy till and are undulating to gently rolling in relief (Kjearsgaard 1972). The Codesa Complex develops a moisture barrier at the interface with the underlying till and is therefore more productive than similar sandy soils without this feature (Kjearsgaard 1972). These soils, however, are not suitable for continuous agricultural production due to concerns with wind erosion of the sandy surface

(Kjearsgaard 1972). The majority of the soils within the series are classified as Brunisolic; however some soils may be classified as Regosolic based on the lack of soil horizination and pedogenic development (Kjearsgaard 1972). Both of the 8-yr-old plantations are located on the Mapova soil series which occur in association with the Tawatinaw series and Codesa Complex. Mapova soils are composed of till materials of loam texture, nearly level to gently undulating topography, are poorly drained, have dull colours and brownish mottles, are classified as Gleysolic soils and may have 15-20 cm of organic matter accumulation at the surface (Kjearsgaard 1972). The 6-yr-old plantations and one of the 4-yr-old plantations are situated on the Codesa Complex overlying the Tolman Series as described above. The second 4-yr-old plantation is located on the Nestow Series. This series has loamy sand textures originating from alluvial and aeolian deposits, is rapidly drained and occurs on gently rolling topography (Kjearsgaard 1972). The solum is slightly acidic with no presence of carbonates in the parent material which leads to sites dominated by a Degraded Dystric Brunisolic soil (Kjearsgaard 1972, Table 4.2).

4.2.2. Sampling design

The chronosequence of plantations studied were selected from all plantations established by Al-Pac since 1993. Two types of hybrid poplar clones were used: Walker (*Populus deltoides* x *Populus x petrowskyana* cv. Walker) and Northwest (*Populus balsamifera x Populus deltoides* cv. Northwest). Two replicates of 4 plantation ages (4-, 6-, 8-, and 13-yr old) were identified. The 13-yr-old age class is pseudo-replicated (both plots within the same stand) because there was only one 13-yr-old plantation stand established. Soil gas efflux was sampled using a static chamber technique on 21 June, 7 July, 19 July, 9 August and 22 August 2005. In addition, soil core samples were collected on 21 June and 19 July 2005 to determine soil properties, fine root biomass and nutrient content as described below.

All plots were placed at least 10 m inside the stand to minimize any edge effect. Within each stand, two 1 x 1 m plots were established in mid-May 2005: one control plot and one root excluded or trenched plot. The plots (control and trenched) were all placed systematically between four tree stems in each plantation to avoid inducing error in soil respiration measurements resulting from differences in the distance of the plot to tree stems (Fig. 4.2). Trenching for the root exclusions were installed to a depth of 40 cm, within which most of the root growth and activity occurs. The walls of the intact plot were lined with polypropylene tightly woven landscaping fabric which allowed for transfer of soil water and gas but impeded the penetration of roots into the plot. The trenches were then carefully backfilled with original soil material replaced in its original order to minimize disturbance to the site profile. Control plots were placed approximately 10 m away. Both the control and trenched plots were maintained free of herbaceous vegetation for the entire duration of the study with weekly or bi-weekly applications of the herbicide Roundup® (Glyphosate, 540 g L^{-1}, diluted 10:1 with water, application rate 5 L ha^{-1}), as required. Trenched plots were not sampled for 1 month for the soil system to regain equilibrium and avoid error originating from the disruption of the site.

4.2.3. Heterotrophic (R_h), root (R_r) and total soil (R_s) respiration

Root respiration (R_r) is the contribution of CO_2 derived from plant roots and micro-organisms dependent on root exudates to total soil respiration (R_s), and heterotrophic respiration (R_h) is the contribution of microbial activity to R_s, where R_s is the sum of R_r and R_h. These respiration rates were derived from CO_2 samples collected using a static chamber technique on 21 June, 7 July, 19 July, 9 August and 22 August 2005. Plastic soil collars were fitted to the diameter of Hutchinson chambers (Fig. 4.3) that were placed in the center of trenched and control plots within each stand. The collars were pushed approximately 3 cm into the soil and remained in place for the entire sampling period to avoid error induced from soil disruption which occurs when placing the collars in the soil (soil flushing; see Wang et al. 2005). Gas samples were collected by a gas-tight syringe prior to placing the chamber over the collars (ambient condition), and through a rubber septum 5, 10 and 20 minutes after placing the chamber over the collar. Duplicate samples were collected for each time interval and stored in evacuated 10-mL soda glass Isomass Exetainers®. Gas samples were collected on fair weather days to avoid the confounding effect of increased soil respiration in response to increases in soil moisture. The vials were over-pressured (20 mL) to ensure positive pressure for successful analysis on a Varian CP-3800 (Varian Canada, Mississauga, Canada) gas chromatograph equipped with three detectors: an Electron Capture Detector (ECD) for quantification of nitrous oxide (N_2O), a Flame Ionization Detector for methane (CH_4) detection and a Thermal Conductivity Detector (TCD) for carbon dioxide (CO_2) determination.

In December 2004, a cross-laboratory calibration of standards was completed with Agriculture and Agri-Food Canada in Lethbridge, Alberta. Fourteen laboratories from across the Canadian prairie region submitted standards to be calibrated against standards developed by the National Oceanic and Atmospheric Administration (NOAA) of the United States Department of Commerce. This calibration was primarily aimed at improving N_2O detection as it is the most difficult of the three greenhouse gases discussed above to be quantified. Once this calibration was complete, the GC was routinely re-calibrated on a bi-weekly basis. A five point calibration was used with three replicate samples at each calibration level. Calibration was deemed acceptable only when an r^2 greater than 0.99 was achieved. A sample calibration curve for the TCD from the Varian CP-3800 gas chromatograph is presented in Fig. 4.4.

Gas concentrations determined by GC for the 0, 5, 10 and 20 minute samples were then transformed into respiration rates using Equations 1 (Nakayama 1990) and 2. A mole of an ideal gas at standard temperature (0 °C) and pressure (101.3 kPa) occupies a volume of 22.4 L, which can be converted to 44.6 moles m^{-3}. This ideal volume is then corrected for the actual air temperature at the time of sampling and used to calculate the efflux.

$$T = 44.6 mol \cdot m^{-3} * \frac{273.15}{(273.15 + ActualAirTemperature)} \qquad \text{Equation 1}$$

$$Efflux = \frac{\Delta C * T * V}{\Delta t * A} = \frac{\Delta C * T * h}{\Delta t} \qquad \text{Equation 2}$$

Where ΔC = change in CO_2 concentration in the selected time interval (μmol mol^{-1})

T = temperature adjustment for molecular volume of gas (mol m^{-3})

V = volume of static gas chamber (m^3)

A = area of ground covered by static gas chamber (m^2)

h = height of Hutchinson chamber (m)

Δt = time interval (s)

The concentrations of CO_2 at time zero and the 5 min interval were selected to compute the respiration values to avoid the plateau effect which develops when CO_2 concentrations within the chamber become too high and the slope of CO_2 increase over time becomes non-linear due to differences in the concentration gradient between the soil and the air in the chamber (Fig. 4.5).

Total soil respiration was the efflux determined in the control plots. Heterotrophic respiration was the efflux measured in the trenched plots. These values were corrected for the excessive release of CO_2 from the accelerated decay of fine roots caused by trenching by applying a correction factor derived from Lavigne et al. (2003). Root respiration was determined by subtracting R_h from R_s.

4.2.4. Correction for rapid decomposition of fine roots in trenched plots

Trenched plot respiration measurements were corrected for decomposition of killed roots from trenching. Trenching kills the tree roots entering the plot, making them susceptible to faster decomposition. This additional decomposition (that portion above and beyond the natural rate of root turnover) must be accounted for in calculating heterotrophic respiration from the trenched plots. Fine root biomass (roots < 2 mm diameter) was determined from soil cores collected in the field on 19 July from all sites. Intact cores were collected for the 0-10 and 10-20 cm increments in control and trenched plots. Quantification of fine roots was completed by carefully removing all fine roots from the soil cores by sequential sieving. This involved a series of sieves stacked together with a bin to catch the finest materials at the bottom of the sieves. Roots were removed with tweezers from all sieves and the bin, washed and weighed fresh, dried at 65 °C for 48 hrs and re-weighed to obtain oven-dry mass. Results were averaged for each plot and scaled up to a 1 m^2 area for analysis by multiplying the average weight of oven-dry fine roots per core by the surface area of the core.

Correction factors were computed using the method developed by Lavigne et al. (2003) who used Equation 3 to calculate heterotrophic respiration from efflux measured in trenched plots. Lavigne's et al. (2003) correction factor (cf) compensated for increased decomposition of severed roots.

$$\text{annual } R_h = AF * (\text{annual } R_t) \qquad \text{Equation 3}$$

Where:

AF (Adjustment Factor) = 1 - annual decomposition rate constant

Using this equation and data presented in Table 4 of Lavigne et al. (2003), I can calculate the adjustment factors used for each site in their experiment. To have a better estimate of the adjustment factors, I calculated adjustment factors for each of Lavigne's et al. (2003) site and year, then computed the mean adjustment factor for each of the three sites (mean of the two years reported by Lavigne et al. 2003). The mean adjustment factors were 0.7733 for the cool site, 0.6518 for the mid-transect and 0.6313 for the warm site in their experiment. A relationship between adjustment factor and fine root biomass (Equation 4) is presented in Lavigne et al. (2003). Equation 4 is based on work by Epron et al. (1999) and indicates an annual fine root decomposition rate constant of 30%.

$$cf = 0.3 * B_{fr} \qquad \text{Equation 4}$$

Where: cf = correction factor (kg C m^{-2} $year^{-1}$)

B_{fr} = fine root biomass (kg C m^{-2} $year^{-1}$)

Annual correction factors calculated by Lavigne et al. (2003) allow us to solve Equation 4 for B_{fr}, which describes the relationship between correction factor and B_{fr} which can then be used to calculate correction factors for the Al-Pac study sites based on fine root measurements taken in summer 2005. The correction factors extrapolated from this relationship can then be applied to respiration rates in the trenched plots to estimate R_h for each plot. Calculations can be seen in Appendix I. Correction factors are presented in Table 4.3

4.2.5. Soil temperature and volumetric water content

Both 13-yr-old plantations, one of the 8-yr-old plantations and one of the 4-yr-old plantations were monitored for soil temperature at 10 cm with type T (copper-constantan) thermocouples (Omega Engineering, Montreal, Canada) and data-logged with Campbell Scientific CR10X dataloggers (Campbell Scientific, Inc., Logan, UT, USA). Soil temperature was measured and recorded every 10 minutes, the daily minimum and maximum and hourly temperature averages were also recorded. The remaining sites were equipped with HOBO H8 Temperature loggers on 12 June 2005 placed at a 10 cm depth and programmed to record soil temperature at 1 hr intervals. Volumetric water content was measured using Campbell Scientific CS616 water content reflectometers (Campbell Scientific, Inc., Logan, UT, USA) in the same plots that were monitored with type T thermocouples and datalogged with CR10X dataloggers. No water content instrumentation was placed in the 6-yr-old plantations due to logistical constraints. The reflectometers were inserted horizontally using a CS615 installation kit at the same depth as for the soil temperature measurement (10 cm depth), in an exposed soil profile. The hole was then backfilled with original soil material in its natural order to minimize disturbance. The water content reflectometer derives the water content information based on the probe sensitivity to the dielectric constant of the medium surrounding the probe rods. The CS616 water content reflectometers have an accuracy of ±2.5% and a resolution of approximately 0.1% (Campbell Scientific, Inc. 2002).

4.2.6. Tree measurements and biomass calculations

There were two marking systems used to install the plantations studied although both were designed with a 3 x 3 m spacing. Six of the fields were marked in only a single direction resulting in variable alignment across rows, while the second system cross marked the planting spots in two directions resulting in a perfect grid layout. Regardless of the marking system, all fields had a tree density of 1111 stems ha^{-1}. Tree heights and diameter at breast height (DBH, 1.3 m up the stem of the tree from the ground) were measured for all plantations. With the exception of the 13-yr-old plantations, where all trees within a pre-existing plot were measured, three grids of 12 trees were established randomly within the plantations and measurements were recorded. The DBH measurements were made with a diameter tape and the heights were measured with a telescoping surveying rod for trees less than 4 m tall and a Vertex III laser hypsometer (Haglof, Sweden) for trees taller than 4 meters. Tree biomass calculations are based on equations developed in hybrid poplar plantations in eastern Ontario using 528 observations from 18 clones subjected to increment sampling and destructive sampling (Ontario Ministry of Natural Resources 1991).

4.2.7. Laboratory analysis

Air-dried mineral soil samples were used to determine total organic C concentrations for each soil horizon in the eight research plots. Total organic C (TOC) was determined using a Carlo-Erba NA1500 CNS elemental analyzer (Carlo Erba Instruments, Milano, Italy).

Particle-size analysis was completed to determine soil texture for each soil horizon of the eight research plots. The hydrometer method was used (Sheldrick and Wang 1993) with no samples receiving pre-treatments as the soil contains no carbonates and organic C concentrations were low. Soil pH was also determined for all soil horizons with both water and 0.1 M calcium chloride ($CaCl_2$) solution. Air-dried soil samples were used at a ratio of 1:1 (10 g soil: 10 mL deionized water or $CaCl_2$) for determination of pH. Samples were mixed in Dixie® cups, allowed to stand for 10 minutes as per Thomas (1996) and analyzed with a Piccolo® 2 portable pH electrode (Hanna Instruments, Laval, Canada) that has a resolution of 0.01.

Soil bulk density for the 0-10 and 10-20 cm depth intervals was calculated using the intact cores collected for the fine root analysis (Table 4.3). Core fresh weights were recorded and sub-samples of soil from the cores were removed during fine root analysis and dried at 105 °C for 24 hrs to determine gravimetric moisture content. Bulk density was calculated as oven-dry mass of soil core (g) divided by core volume (cm^3).

4.2.8. Statistical analysis

Data was analyzed statistically using the Statistical Analysis Software (SAS Institute 1999). The experiment is a Completely Randomized Design with Repeated Measures. All data (root, heterotrophic and total soil respiration) was analyzed according to the following model using the *Proc GLM* (General Linear Model) procedure with the *Repeated* option:

$$Y_{ijk} = \mu + A_i + \varepsilon_{j(i)} + D_k + DA_{ik} + \varepsilon_{ijk}$$

Where:

Y_{ijk} = dependant variable (R_r, R_h or R_s)

μ = overall mean

A_i = the *i*th stand age (4, 6, 8, 13) (fixed factor)

$\varepsilon_{j(i)}$ = the *j*th stand within the *i*th stand age (1, 2, 3, 4, 5, 6, 7, 8) and is used as the error term to test for effect of stand age

D_k = the *k*th date (21 June, 7 &19 July, 9 & 22 August) (fixed factor)

DA_{ik} = the interaction of date * age

ε_{ijk} = random error associated with the stand age * stand * date interaction

The age factor is fixed, thus limiting the applicability of the results from this analysis to the research plots studied. Statistical differences between plantation age for soil moisture, soil temperature, tree height and tree DBH and respiration rates (R_r, R_h or R_s) were elucidated with Tukey's Studentized Range Test using $\alpha = 0.05$ for significance. The *Printe* option in the repeated measures analysis produced a Sphericity test which was used to verify the assumption a compound symmetry of the covariance structure. The ANOVA assumption of normality was assessed using the SAS software version 9.1 *Proc UNIVARIATE* function with the Kolmogorov-Smirnov and Shapiro-Wilk tests for normality (data not shown). All data conformed to a normal distribution except for the root respiration rates (Shapiro-Wilk test $p = 0.009$). A square root data transformation step was used prior to data analysis to obtain a normal distribution for root respiration only.

4.3. Results

4.3.1. Soil temperature and volumetric water content

Soil temperature rose gradually from 13 June 2005 until mid-July and then decreased from mid-July until the end of August (Fig. 4.6a). This closely followed the seasonal air temperature pattern (data not shown). The 4-yr-old stand had the highest average soil temperature of 15.9 ± 0.23 °C (mean ± 1 SE) across the 80 days of measurement, while the 13-, 8- and 6-yr-old stands had an average soil temperature of 14.3 ± 0.18, 13.0 ± 0.14 and 13.3 ± 0.14 °C, respectively. The age effect on soil temperature was highly significant ($p < 0.0001$) and the 4-yr-old plantation differed significantly from all other sites, as did the 13-yr-old. The 8- and 6-yr-old stands differed significantly from the other two ages; however they were not significantly different from each other. Soil volumetric water content was consistently lowest in the 13-yr-old plantation, intermediate in the 8-yr-old stand and highest in the 4-yr-old plantation (Fig. 4.6b). The average moisture content in the 13-, 8- and 4-yr-old stands were (mean ± 1 SE) 0.24 ± 0.004, 0.33 ± 0.004 and 0.37 ± 0.005, respectively. All three plantation ages were statistically different ($p < 0.0001$) from each other for soil moisture content and soil moisture content responded to precipitation rapidly. Soil water was drawn down by evapotranspiration, and water retention in the soil was likely affected by differences in soil texture between the different plantations (see Table 4.2 for soil texture data).

4.3.2. Tree measurements and biomass

Tree height and DBH both increased with tree age in the studied plantations, and the age-classes were significantly different from one another ($p < 0.0001$). The 13-yr-old plantation was tallest (13.6 ± 0.24 m) and had the largest DBH (11.9 ± 0.36 cm) while the 4-yr-old plantation was the shortest (3.8 ± 0.18 m) and had the smallest DBH (3.4 ± 0.03 cm) (Fig. 4.7). Tree biomass C also increased with plantation age and ranged from 1.07 Mg ha^{-1} to 17.07 Mg ha^{-1} in the 4- and 13-yr-old plantations, respectively.

4.3.3. Soil respiration

Root respiration (R_r) was higher on 7 July 2005 than on the other four sampling dates (Fig 4.8a, Note: Trenching occurred in mid-May 2005). Root respiration averaged over all sites for the 5 sampling dates revealed a significantly higher respiration rate (1.1 ± 0.26 µmol m^{-2}s^{-1}) on the 7 July sampling date. The 21 June, 9 August and 22 August sampling dates were intermediate (0.9 ± 0.13 µmol m^{-2}s^{-1}, 0.5 ± 0.10 µmol m^{-2}s^{-1} and 0.6 ± 0.10 µmol m^{-2}s^{-1}, respectively) but not significantly different from any other sampling dates. The 19 July (0.4 ± 0.08 µmol m^{-2}s^{-1}) sampling date was significantly lower only from the 7 July measurement. No trend was apparent and no significant differences were observed between the different stand ages ($p = 0.863$) in the chronosequence; however the effect of date was statistically significant ($p = 0.045$).

Within the sampling dates there were no significant differences between the plantation ages and the data did not show any trends. On 21 June, R_r ranged from 0.6 ± 0.56 µmol m^{-2}s^{-1} in the 6-yr-old plantation to 1.2 ± 0.34 µmol m^{-2}s^{-1} in the 8-yr-old stand. On 7 July, R_r was lowest in the 13-yr-old stand (0.5 ± 0.26 µmol m^{-2}s^{-1}) and highest in the 8-yr-old plot (1.7 ± 0.08 µmol m^{-2}s^{-1}). The 19 July measurements showed a very small range (0.34 µmol m^{-2}s^{-1}) going from 0.3 ± 0.10 to 0.6 ± 0.07 µmol m^{-2}s^{-1} in the 8- and 13-yr-old plantations, respectively. Root respiration ranged from 0.3 ± 0.19 µmol $m^{-2}s^{-1}$ in the 6-yr-old site to 0.8 ± 0.05 µmol $m^{-2}s^{-1}$ in the 13-yr-old site on 9 August. R_r was lowest in the 4-yr-old plantation (0.3 ± 0.25 µmol $m^{-2}s^{-1}$) and highest in the 6-yr-old plantation (0.8 ± 0.15 µmol $m^{-2}s^{-1}$) on 22 August.

Heterotrophic respiration (R_h) appeared to be more stable throughout the sampling period; however there was a slight decrease from the start to the end of the study (Fig. 4.8b). Differences were found between the sampling dates ($p = 0.011$) where the highest R_h was 1.4 ± 0.10 µmol $m^{-2}s^{-1}$ (7 July) and the lowest R_h was 0.7 ± 0.05 µmol $m^{-2}s^{-1}$ (22 August), respectively. The 7 July, 21 June (1.2 ± 0.03 µmol $m^{-2}s^{-1}$) and 9 August (1.2 ± 0.08 µmol $m^{-2}s^{-1}$) sampling dates were statistically different from the 22 August measurement, while the 19 July (1.1 ± 0.09 µmol $m^{-2}s^{-1}$) sampling date was not significantly different from any other dates. Similar to the root respiration measurements, no significant differences were identified between the plantation ages ($p = 0.687$).

Ranges in R_h on the five sampling dates were very small. On 21 June, R_h ranged from 1.1 ± 0.001 µmol $m^{-2}s^{-1}$ in the 13-yr-old site to 1.3 ± 0.30 µmol $m^{-2}s^{-1}$ in the 4-yr-old site. There was a difference of 0.35 µmol $m^{-2}s^{-1}$ between the 6- and 8-yr-old plantations (1.2 ± 0.48 and 1.6 ± 0.27 µmol $m^{-2}s^{-1}$, respectively) on 7 July. R_h was lowest (0.8 ± 0.09 µmol $m^{-2}s^{-1}$) in the 4-yr-old plantation and highest (1.2 ± 0.03 µmol $m^{-2}s^{-1}$) in the 6-yr-old plantation on 19 July. The R_h on 9 August went from 1.0 ± 0.07 to 1.4 ± 0.22 µmol $m^{-2}s^{-1}$ in the 4- and 8-yr-old plantations, respectively. Finally, R_h ranged from 0.6 ± 0.02 µmol

$m^{-2}s^{-1}$ in the 6-yr-old plantation to 0.8 ± 0.09 μmol $m^{-2}s^{-1}$ in the 4-yr-old plantation on 22 August.

Total soil respiration (R_s) was highest on 7 July (2.5 ± 0.27 μmol $m^{-2}s^{-1}$), intermediate on 21 June (2.2 ± 0.14 μmol $m^{-2}s^{-1}$) and 9 August (1.7 ± 0.11 μmol $m^{-2}s^{-1}$), and lowest on 22 August (1.3 ± 0.05 μmol $m^{-2}s^{-1}$) (Fig 4.8c). Significant differences were found between the sampling dates ($p < 0.0001$), but not between the different plantation ages ($p = 0.659$). R_s measurements on 7 July were significantly different from that on 19 July, 9 August and 22 August. Soil respiration measured on 21 June was similar to those on 7 July and 9 August, but significantly greater than those on 19 July and 22 August.

The average contribution of R_h to R_s across all ages ranged between 0.58 ± 0.058 (22 August) and 0.72 ± 0.032 (19 July); however no significant differences were found between plantation ages ($p = 0.922$) or between sampling date ($p = 0.195$). The contribution of R_h to R_s ranged from 0.53 to 0.72 in the 4-yr-old site, 0.43 to 0.80 in the 6-yr-old plantation, 0.47 to 0.79 in the 8-yr-old age-class and 0.53 to 0.76 in the 13-yr-old plantation across the five sampling dates. The average proportion of R_h to R_s across all sites and sampling dates was 0.63 ± 0.026 (Fig. 4.9a). When the mean contribution of R_h to R_s by plantation age is plotted, we observed a negative linear relationship, indicating a decrease in the contribution of heterotrophic respiration to soil respiration ($r^2 = 0.7694$, Fig. 4.9b); however this relationship was not statistically significant ($p = 0.123$).

4.4. Discussion

Logically we would expect higher soil temperatures in the youngest plantation, and lower soil temperatures in the older plantations due to differences in soil exposure. Older stands generally have more leaf area and more established vegetation, leading to shading of the soil surface by live plants and by surface litter. Our data clearly shows that the 4-yr-old stand (Walker clone) had the warmest soil temperatures, followed by the 13-yr-old plantation (Fig. 4.5a). This irregularity can be explained by considering two important factors: 1) light penetration, and 2) soil volumetric water content. In the 13-yr-old plantation, periodic mowing and removal of grasses, shrubs and competing vegetation expose the soil surface. The removal of this understory vegetation exposes the soil surface to more direct and indirect sunlight, creating the potential for greater heating. Moreover, the trees in the13-yr-old plantation have lost the majority of their lower branches due to self-pruning (personal observation). This has also created more space for light penetration to the soil surface. Furthermore, the 13-yr-old site, apart from being older, is composed of Walker poplar, which grows much taller and with a narrower crown (North Dakota State University 2006) than the Northwest poplar clone that was planted in the 6- and 8-yr-old plantations which is distinguished by wide-angled branches (Alberta Agriculture, Food and Rural Development 2001). These factors explain how the increased sunlight penetration might lead to higher daily average soil temperatures in the 13-yr-old stand. The factors controlling soil temperature in the 6- and 8-yr-old plantations are much different. These two age-classes were not maintained as per the oldest plantation in terms of controlling the ground vegetation. The ground is densely covered by a variety of wild grasses and some residual crop plants from previous land-uses.

Furthermore, at this stage, the Northwest clone retains its lower branches which also aid in intercepting much of the direct sunlight, further shading the soil surface. Slight differences in tree density between the different plantations could also have affected soil temperatures. Planting densities ranged from 2.5 x 2.5 m to 3 x 3 m as operational planting standards were modified, which could result in greater light transmittance to the soil surface in plantations of lower densities. The final factor that may explain the temperature difference is the soil volumetric water content. Fig. 4.5b shows soil volumetric water content is lowest in the 13-yr-old plantation and increases with decreasing age of the plantation. Water use by plants is determined by incoming radiation (specifically the portion used for evaporation of water), saturation deficit, leaf area index and plant species characteristics (Radersma et al. 2006). All these characteristics except leaf area index are similar across the different plantation ages. Since the oldest trees have greater biomass (Fig. 4.6), there is likely a higher water requirement/uptake in the oldest plantation due to increased evapotranspiration, and hence a decreasing soil water content with increasing plantation age. Due to the high energy requirement to heat water, a soil with less water content will warm faster (due to lower heat capacity). This may also contribute to the soil in the 13-yr-old stand being the second warmest because having a lower water status enables the soil to warm more.

I hypothesized that root respiration would become an increasingly larger proportion of total respiration as plantation age increased; therefore heterotrophic respiration contribution would decrease. This does not, however, imply a decrease in net heterotrophic respiration. On the contrary, heterotrophic respiration is also likely to increase with plantation age due to larger quantities of litter inputs aboveground and increased rhizodeposition related to tree growth and root production belowground; the supply of substrates from aboveground litter and root litter fuel heterotrophic respiration (Bhupinderpal-Singh et al. 2003). Furthermore, litter quality will be a critical factor in determining heterotrophic respiration rates in the plantations. Litter inputs with a small C:N ratio will be decomposed faster than litter inputs with a greater C:N ratio (see Parmelee et al. 1989). Therefore if the C:N ratio of the litter changes with plantation age, respiration rates will be affected accordingly. No relationship was found between R_h or R_r and plantation age; however a weak trend ($p = 0.123$, $r^2 = 0.769$) showing a decreasing contribution of heterotrophic respiration to soil respiration with increasing plantation age was noted. These findings are similar to those reported by Bond-Lamberty et al. (2004a) where the contribution of heterotrophic respiration to soil respiration in a chronosequence of black spruce stands decreased from 100% in a recently burned site to 60-65% in a 21-yr-old stand; however the reverse was true in later succession as the contribution of R_h then increased again to 85-95% in a 152-yr-old stand. Saiz et al. (2006) reported an increasing trend of heterotrophic respiration contribution to total soil respiration with stand age in a sitka spruce (*Picea sitchensis* (Bong.) Carr.) chronosequence. The authors reported an increase of the relative contribution of R_h to R_s from 40.7% in the youngest stand (10-yr-old) to 50.3% in the oldest stand (47-yr-old) which they related to higher root activity in younger stands. We have a very small range of plantation ages (4 to 13 years) while the two aforementioned studies consider chronosequences that are 3 to 10 times longer. This may explain the relatively slow decline in R_h contribution and relatively small difference between the youngest and oldest stands in the poplar chronosequence.

Another factor that may mask the change in contributions of R_r and R_h to R_s over the chronosequence is the soil type. In addition to the inherent differences in soil temperature regime and volumetric water content between the four different plantation ages, the soils were classified differently (Table 4.1). An analysis of the data which groups the Gleysolic soils together as soil type 1 and the Brunisolic and Regosolic soils together as soil type 2 (data not shown) revealed an effect of soil type on autotrophic respiration ($p = 0.041$) but no significant effect on heterotrophic ($p = 0.393$) and total soil respiration ($p = 0.062$). The current study was not designed to test for the effect of soil type on the different components of soil respiration; however, taking into account the preliminary results shown above, careful consideration should be taken to avoid such confounding factors in future research or to incorporate them into the statistical design.

Our reported values of heterotrophic respiration may underestimate the actual heterotrophic respiration on the sites due to the calculation of the correction factors, thus decreasing the proportion of soil respiration contributed by roots. Estimates of R_h have decreased by an average of 12% when corrections are made for decay of roots (Subke et al. 2006). Although the correction factors were based on measurements of fine root biomass in each individual plot, they were also based on an average (i.e. constant) decomposition rate of 30% yr^{-1} from a balsam fir ecosystem. Usman et al. (2000) reported fine root (0-1 mm) decomposition rates of 47 and 45% yr^{-1} in a *Quercus* *leucotrichophora* A. Camus stand and a *Pinus roxburghii* Sarg. stand, respectively, occurring in a humid climate regime. A higher fine root decay rate of 46.7% yr^{-1} was reported in a silver maple (*Acer saccharinum* L.) stand in Iowa, USA (Dornbush et al. 2002). These studies indicate that a 30% yr^{-1} decomposition rate may be conservative for a hybrid poplar plantation. Moreover, decomposition rates during the growing season when soils are warm are bound to be higher than during the winter months when soils are frozen. Since 30% is simply an annual average, the decomposition was likely much higher in the plots at the time efflux measurements were made. For example, if the decomposition rate was doubled to 60% yr^{-1} for the growing season, values of heterotrophic respiration would have decreased by a range of 10% in the 13-yr-old stand to 2% in the 4-yr-old stand. Adjustments to single measurements of soil respiration may not be significantly affected by this factor; however the computation of annual respiration rates could significantly be altered. This illustrates the importance of decomposition rates in these types of calculations and the value of determining site specific belowground decomposition rates to ensure more reliable estimates of the contribution of root decay to soil CO_2 efflux after trenching. The correction factors calculated for our chronosequence of hybrid poplar plantations decreased heterotrophic respiration by 14-22%. This corresponds extremely well with Epron et al. (1999) who reported the contribution of root decay to CO_2 efflux in trenched plots of 14-24% in a beech forest in eastern France.

The mean contribution of R_h to soil respiration in this study (63 ± 2.6%) falls within the range of 50 – 70% reported by Bond-Lamberty (2004b) in a review of data from 54 forested sites, but is slightly higher than an average contribution of 51.4% from a review of 37 forested sites reported by Hanson et al. (2000). Numerous partitioning studies have reported values of R_h/R_s well below our current estimate (e.g. 44-48% in Hoberg et al. (2001); 40-45% in Ross et al. (2001); 40% in Epron et al. (1999)), however these recent studies have looked at natural ecosystems of Scots pine, radiata pine and beech forests. The only other study found that examined plantation forests was a gap analysis study by Ohashi et al. (2000) in a 10-yr-old planted Japanese cedar forest in which they reported a R_h:R_s ratio of only 43%. A strikingly different aspect is that this work was done in a chronosequence of hybrid poplar plantations; a type of system not previously studied in respiration partitioning experiments. A recent review by Subke et al. (2006) reported only three studies that have investigated the effect of age on soil respiration partitioning (Bond-Lamberty et al. 2004a; Czimczik et al. 2006; Saiz et al. 2006). These three projects studied natural black spruce and Sitka spruce ecosystems; therefore this study is unique as it is the first to report on hybrid poplar plantations. This is significant because when planted on agricultural lands, fast-growing plantations are believed to be a major potential sink for CO_2 if trees were re-introduced (Albrecht and Kandji 2003). In order to assign C credits with these afforestation activities, proper quantification of the net release of CO_2 to the atmosphere from the soil is crucial. This entails an interpretation of the effects of various biotic and abiotic factors on the contributions of root respiration (R_r) and heterotrophic respiration (R_h) to R_s individually.

R_r was highest in July, followed by a decrease; this phenomenon can likely be explained by high physiological activity related to root growth (Lee et al. 2003). Changes in seasonal contribution of R_r to R_s associated with root construction costs have been reported (Hanson et al. 1993). Fine root activity peaked in March (spring) and September (fall) in a mixed deciduous forest dominated by 50-yr-old tulip poplar (*Liriodendron tulipifera* L.) in Tennessee, USA (Edwards and Harris 1977). Certainly this indicates the importance of tree and root phenology in influencing the partitioning of sources of soil respiration. Most studies focus on the abiotic controls of soil respiration (i.e. soil temperature and moisture content, Davidson et al. 1998; Fang and Montcrieff 2001; Eliasson et al. 2005), partly due to methodological difficulties in assessing biotic controls on soil respiration. Moreover, there are very few reports that elucidate the importance of phenology and photosynthate movements on soil respiration rates (Ekblad and Hogberg 2001; Yuste et al. 2004; Tang et al. 2005); even though studies have concluded that more research into these mechanisms is required (Bhupinderpal-Singh et al. 2003; Scott-Denton et al. 2006). New developments to describe these processes are needed to extend our understanding of the biotic controls on soil respiration in various ecosystem types.

4.5. Conclusions

Plantations of differing ages were shown to have differences in soil temperature and soil moisture content. Soil temperature did not decrease with increasing stand age as was anticipated; however differing maintenance patterns across the plantations and tree phenological characteristics likely contributed to this unusual trend. The hypothesis of increasing root respiration along the chronosequence was not clearly supported by the data; however a weak trend of decreasing contribution of heterotrophic respiration to soil respiration with increasing plantation age was noted. The calculation of correction factors indicates that the trenched plot method was sensitive to the rate of decomposition of roots used in the calculation. This experiment demonstrates clearly the need to further consider the effect of root decomposition, the role this accelerated decomposition plays in soil CO_2 efflux, and the need to develop site-specific correction factors tightly linked to fine root biomass estimates. To meet the Kyoto mandate, Canada must report accurate and verifiable estimates of GHG emissions and removals (Vandenbygaart et al. 2004). From a practical point of view, the capability of reporting accurate estimates of GHG emissions and removals from soils in hybrid poplar plantations depends on our ability to measure the contributions of R_r and R_h to R_s and the response of these contributions to environmental changes (soil temperature and water content), which are likely to be enhanced by changes in the global climate.

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Table 4.1. Soil profile description for each research site recorded in October 2005.

Horizon	Depth (cm)	Description
4-yr-old plantation, Replication 1: Gleyed Humic Regosol		
Ah	0-24	Dark grayish brown (10YR 4/2 d); sandy loam; single grain; loose; abundant, fine, random roots and few, medium, horizontal roots; abrupt, smooth boundary; 24-26 cm thick.
Cg	24-110+	Pale brown (10YR 6/3 d); loamy sand; single grain; loose; many, medium to coarse, prominent mottles; few, very fine and fine, random roots.
4-yr-old plantation, Replication 2: Orthic Sombric Brunisol		
Ah	0-29	Dark grayish brown (10YR 4/2 d); silt loam; weak, medium granular; friable; abundant, fine, random, inped and exped roots and few, medium, horizontal, exped roots; abrupt, smooth boundary; 29-31 cm thick.
Bm	29-85	Pale brown (10YR 6/3 d); silt loam; abundant, fine, random roots; abrupt, smooth boundary; 56-59 cm thick.
C	85-110+	Light brownish gray (10YR 6/2 d); loam.
6-yr-old plantation, Replication 1: Gleyed Melanic Brunisol		
Ah	0-19	Pale brown (10YR 6/3 d); loamy sand; single grain; loose; plentiful, fine, random roots, few, coarse, horizontal roots and few, medium, oblique roots; abrupt, smooth boundary; 19-21 cm thick.
Bm	19-40	Light yellowish brown (10YR 6/4 d); loamy sand; single grain; loose; few, medium, oblique roots, plentiful, fine, random roots; gradual, smooth boundary; 21-28 cm thick.
Cgj	40-140	Yellowish brown (10YR 5/4 d); sand; single grain; loose; common, medium, faint mottles; few, coarse and medium, oblique roots and plentiful, fine, random roots; abrupt, smooth boundary; 100-105 cm thick.
Cg	140+	Very pale brown (10YR 7/4 d); sandy loam; loose; many, medium to coarse, prominent mottles.

6-yr-old plantation, Replication 2: Orthic Humic Gleysol

Ah	0-17	Dark gray (10YR 4/1d); loam to sandy loam; weak, medium granular; very friable; abundant, fine, random, exped roots, plentiful, medium, random, exped roots and few, coarse, lateral, exped roots; abrupt, smooth boundary; 17-20 cm thick.
Ahejg	17-34	Dark grayish brown (10YR 4/2 d); loamy sand; weak, fine platy; very friable; common, medium, faint mottles; plentiful, fine, random, exped roots and few, medium, oblique, exped roots; clear, irregular boundary, 17-22 cm thick.
Btjg	34-43	Grayish brown (10YR 5/2 d); sandy loam; weak, fine, subangular blocky; very friable; common, medium, distinct mottles; plentiful, medium, oblique roots and plentiful, fine, random roots; abrupt, smooth boundary; 9-11 cm thick.
Cg1	43-111	Light brownish gray (10YR 6/2 d); loamy sand; single grain; loose; many, coarse, prominent mottles; few, fine, random roots; clear, smooth boundary; 68-70 cm thick.
Cg2	111-140+	Light gray (10YR 7/2 d); loamy sand; single grain; loose; many, coarse, prominent mottles; water table at 140 cm.

8-yr-old plantation, Replication 1: Orthic Humic Gleysol

Of	11-0	Abundant, fine, vertical and horizontal roots, few, medium and coarse, oblique roots and few, coarse, horizontal roots; abrupt, smooth boundary, 11-15 cm thick.
Ahegj	0-22	Very dark brown (10YR 2/2 d); silt loam; moderate, coarse platy to weak, fine platy; common, faint,fine mottles; plentiful, fine horizontal and vertical roots, few, coarse, horizontal roots and few, medium, oblique roots; gradual, irregular boundary, 22-27 cm thick.
Bg	22-59	Light yellowish brown (10YR 6/4 d); loam; weak, coarse platy; friable; many, medium to coarse, faint mottles; plentiful, horizontal and vertical, fine roots and few, medium, oblique roots; abrupt, smooth boundary; 37-40 cm thick.
Cg	59-109+	Light brownish gray (10YR 6/2 d); silty clay loam; common, faint, medium mottles; plentiful, random, fine roots and few, medium, oblique roots.

8-yr-old plantation, Replication 2: Orthic Humic Gleysol		
Ah	0-20	Dark gray (10YR 4/1 d); silt loam; moderate, fine granular; friable; plentiful, fine, random, exped roots and few, medium, oblique, exped roots; abrupt, smooth boundary; 20-22 cm thick.
Bg	20-61	Light brownish gray (10YR 6/2 d); silty clay loam; amorphous; many, fine, prominent mottles; few, fine, random roots and few, medium and coarse, oblique roots; gradual, smooth boundary; 41-50 cm thick.
Cg	61-110+	Light gray (10YR 7/2 d); loam; amorphous; many, medium, prominent mottles; few, coarse, horizontal roots and few, fine, horizontal roots.
13-yr-old plantation, Replication 1 and 2: Orthic Humic Gleysol		
Ah	0-17	Grayish brown (10YR 5/2 d); sandy loam; single grain; loose; few, very fine, random roots, few, fine, random roots and few, coarse, horizontal roots; clear, wavy boundary; 17-22 cm thick.
Bg	17-70	Light yellowish brown (10YR6/4 d); loamy sand; single grain; loose; many, medium, prominent mottles; few, medium and coarse, horizontal and oblique roots; abrupt, smooth boundary; 53-56 cm thick.
Cg	70+	Light brownish grey (10YR 6/2 d); silt loam.

Table 4.2. Soil characteristics (Horizon- Classified according to the Canadian System of Soil Classification, TOC- Total Organic C, TON- Total Organic N, pH$_{H2O}$ – soil pH in water, pH$_{CaCl2}$ – soil pH in calcium chloride, %clay, silt, sand – textural analysis).

Horizon	Depth (cm)	TOC (%)	pH H_2O	pH $CaCl_2$	% clay	% silt	% sand
4-yr-old plantation, Replication 1: Gleyed Humic Regosol							
Ah	0-24	1.89	6.32	5.49	6.35	21.18	72.47
Cg	24-110+	0.27	7.13	6.10	7.26	11.43	81.31
4-yr-old plantation, Replication 2: Orthic Sombric Brunisol							
Ah	0-29	3.48	6.62	5.86	21.51	61.45	17.04
Bm	29-85	0.47	5.33	4.86	24.41	70.40	5.19
C	85-110+	0.25	7.78	7.06	9.75	41.91	48.34
6-yr-old plantation, Replication 1: Gleyed Melanic Brunisol							
Ah	0-19	0.79	5.50	4.23	4.60	17.93	77.47
Bm	19-40	0.10	6.46	5.02	6.05	15.68	78.28
Cgj	40-140	0.19	6.22	4.80	4.02	8.24	87.74
Cg	140+	0.15	7.57	6.86	7.45	30.87	61.68
6-yr-old plantation, Replication 2: Orthic Humic Gleysol							
Ah	0-17	3.08	7.43	7.01	7.38	16.16	76.46
Ahejg	17-34	0.69	6.40	5.96	7.56	14.68	77.76
Btjg	34-43	0.44	7.70	6.02	12.99	33.73	53.27
Cg1	43-111	0.14	8.02	6.48	4.17	10.36	85.46
Cg2	111-140+	0.10	7.63	7.03	7.18	10.24	82.58
8-yr-old plantation, Replication 1: Orthic Humic Gleysol							
Of	11-0	38.54	7.68	7.11			
Ahegj	0-22	1.63	7.07	6.99	16.54	48.77	34.69
Bg	22-59	0.33	7.08	6.81	14.41	40.82	44.78
Cg	59-109+	0.58	7.20	7.00	38.34	47.57	14.08
8-yr-old plantation, Replication 2: Orthic Humic Gleysol							
Ah	0-20	5.90	7.05	5.63	18.66	57.91	23.43
Bg	20-61	0.78	6.68	6.19	34.19	48.80	17.01
Cg	61-110+	0.30	6.48	6.09	16.10	35.28	48.62
13-yr-old plantation, Replication 1 and 2: Orthic Humic Gleysol							
Ah	0-17	0.94	5.95	4.58	8.94	28.74	62.32
Bg	17-70	0.22	7.05	5.42	6.65	16.55	76.80
Cg	70+	0.32	7.75	7.27	27.42	49.86	22.72

Table 4.3. Soil bulk density for each research site in the hybrid poplar chronosequence for the 0-10 and 10-20 cm sampling intervals.

Plantation Age (years)	Replication	Depth Interval (cm)	Bulk Density (Mg m^{-3})
4	1	0-10	1.24
		10-20	1.46
	2	0-10	0.86
		10-20	0.95
6	1	0-10	1.27
		10-20	1.35
	2	0-10	1.08
		10-20	1.09
8	1	0-10	0.49
		10-20	1.17
	2	0-10	0.98
		10-20	1.30
13	1	0-10	1.29
		10-20	1.40
	2	0-10	1.31
		10-20	1.45

Table 4.4. Fine root biomass and associated correction factors that applied to trenched-plot respiration values to calculate heterotrophic respiration.

Plantation Age	Repetition	Fine Root Biomass ($g\ C\ m^{-2}$)	Correction Factor
4	1	75.9	0.841
4	2	7.7	0.858
6	1	154.3	0.821
6	2	288.4	0.789
8	1	181.1	0.815
8	2	185.6	0.814
13	1	332.5	0.779
13	2	233.6	0.802

Figure 4.1. Location of the research site.

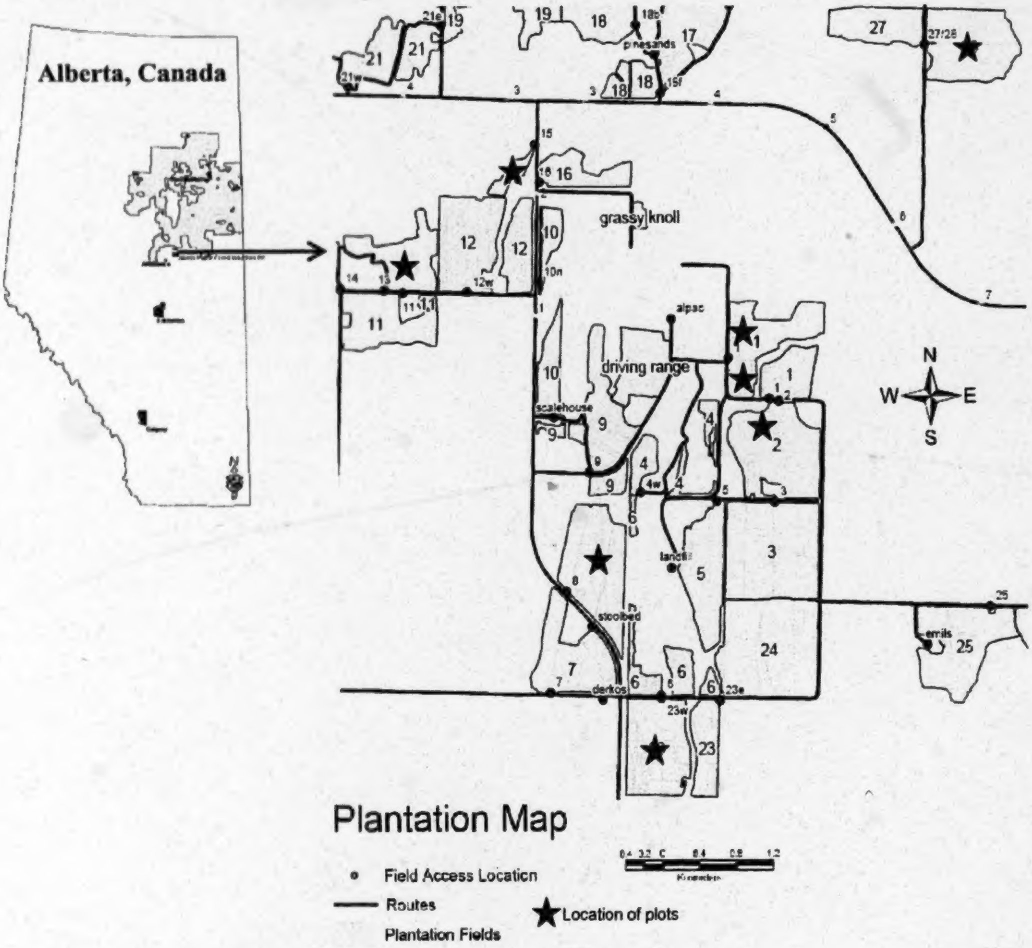

Alberta, Canada
Plantation Map
Field Access Location
Routes
Plantation Fields
Location of plots
N
W
E
S
grassy knoll
driving range
alpac
scalehouse
landfill
stoolbed
derkos
pinesands
emils
27/28
21
21e
21w
19
18
18b
17
16
15
14
13
12
12w
11
10
10n
9
7
6
5
4
4w
3
2
1
23
23w
23e
24
25
27

Figure 4.2. Experimental plot layout. Both control plot and trenched plot respiration measurements were made in the center of a 4 tree planting grid (see collar description in text).

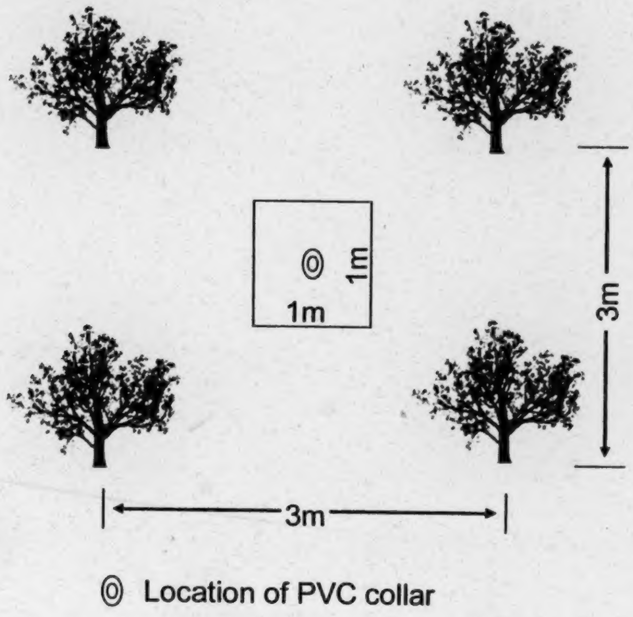
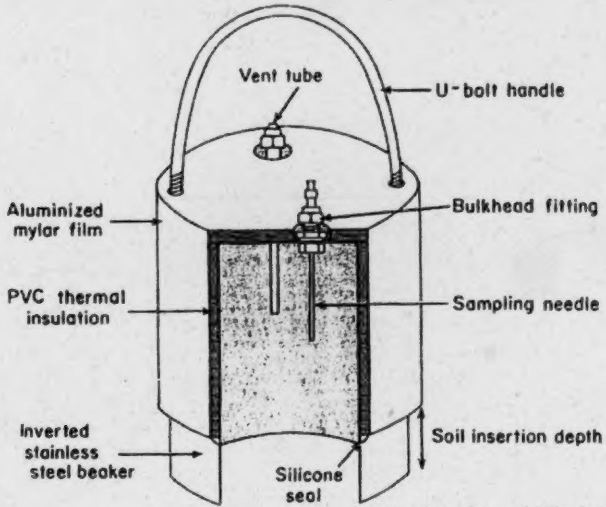

1m
1m
3m
3m
◎ Location of PVC collar

Figure 4.3. A schematic diagram of the Hutchinson static gas chamber.


Vent tube
U-bolt handle
Aluminized mylar film
Bulkhead fitting
PVC thermal insulation
Sampling needle
Inverted stainless steel beaker
Soil insertion depth
Silicone seal

Source: Hutchinson and Mosier 1981

Figure 4.4. Sample calibration curve for the Varian CP-3800 Thermal Conductivity Detector.

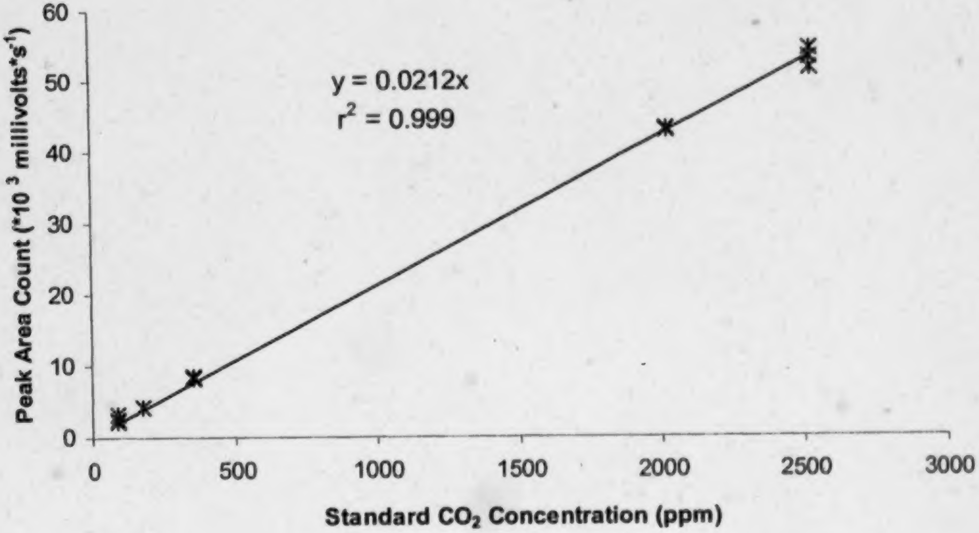


Figure 4.5. Two samples depicting the non-linearity of CO_2 increase in the Hutchinson static gas chambers.

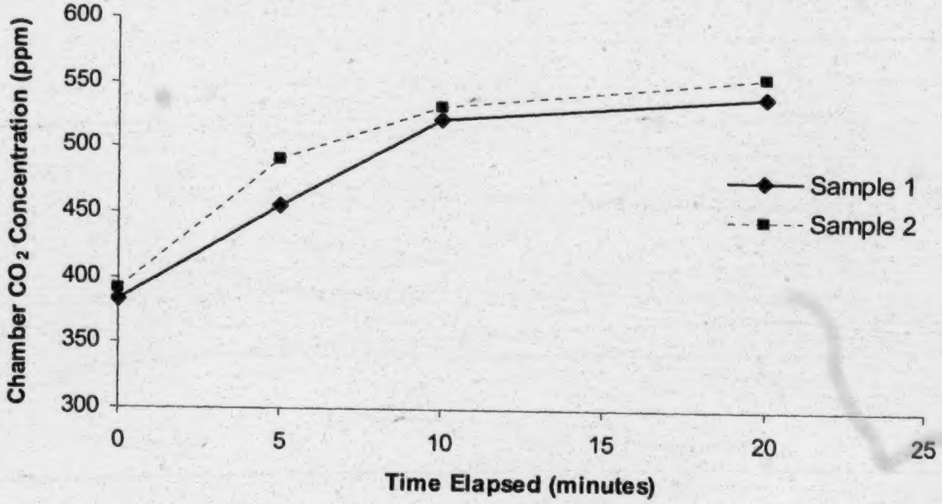


Figure 4.6. a) Soil temperature at 10cm and b) soil moisture content at 10cm (line) and precipitation (bar) across the chronosequence of hybrid poplar plantations in 2005. Note: 4- & 13-yr-old stands were Walker poplar, 6- & 8-yr-old stands were Northwest poplar.

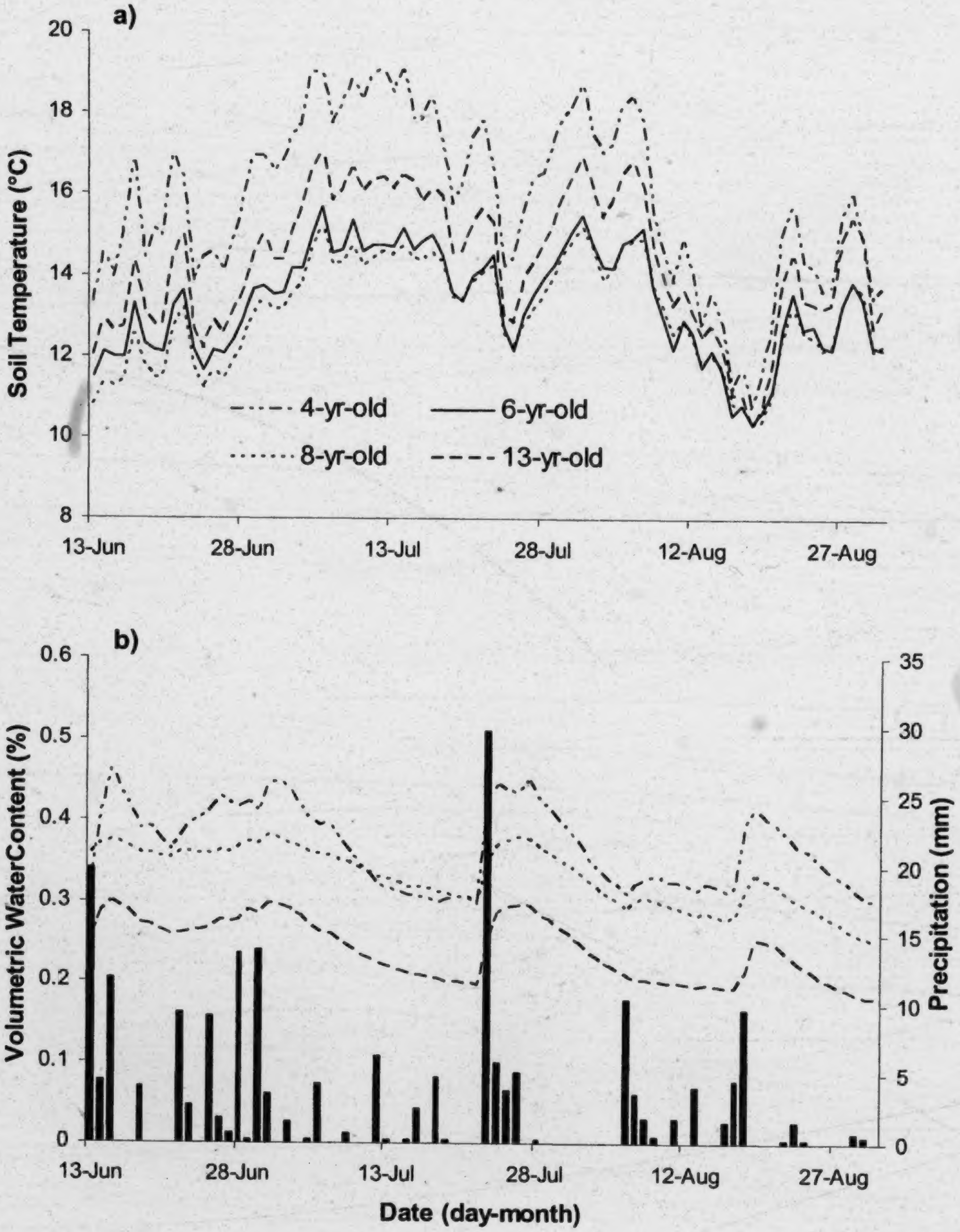


Figure 4.7. Average height, diameter and biomass C on a per hectare basis in the chronosequence of hybrid poplar plantations. Two plantations of each age were sampled. Note: 4- & 13-yr-old stands were Walker poplar, 6- & 8-yr-old stands were Northwest poplar.

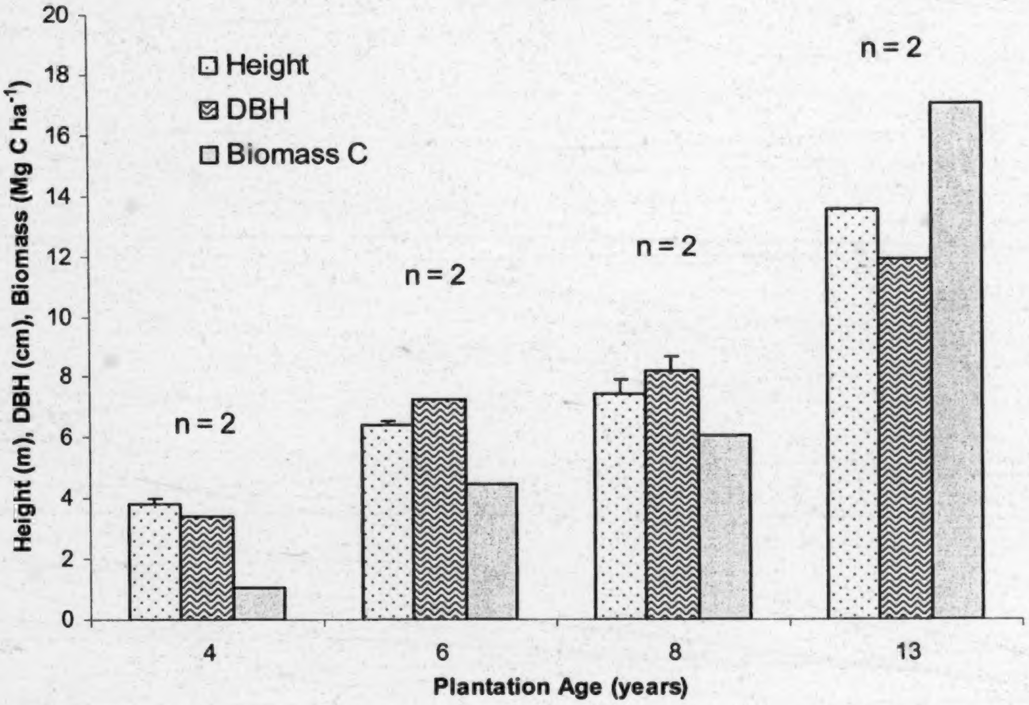


Figure 4.8. Soil respiration measured across the chronosequence and separated into a) root (black bar), and b) heterotrophic (white bar) respiration for the 5 sampling dates. The contribution of both sources to total soil respiration is presented in c). Different uppercase letters denote statistical differences between the sampling dates. Vertical bars indicate +1 SE in a) and b), and +1SE for root respiration and -1SE for heterotrophic respiration in c). Note: 4- & 13-yr-old stands were Walker poplar, 6- & 8-yr-old stands were Northwest poplar.

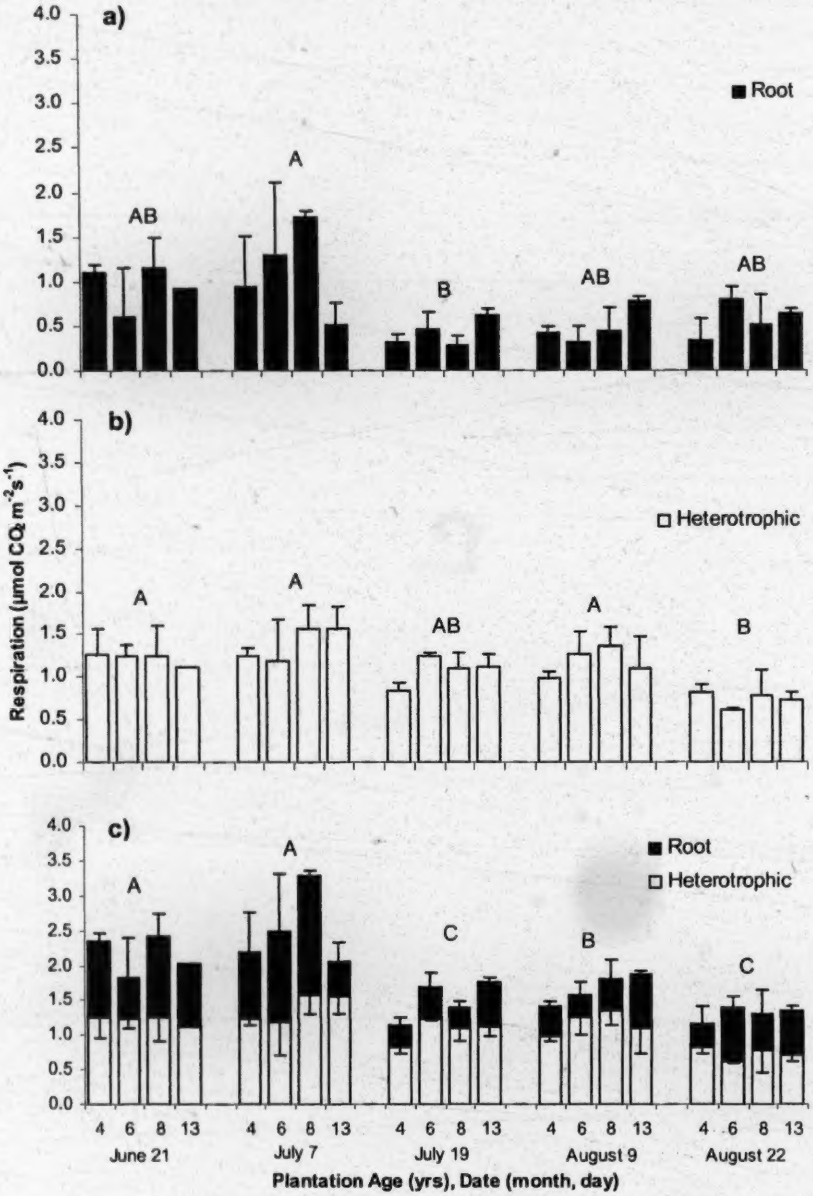
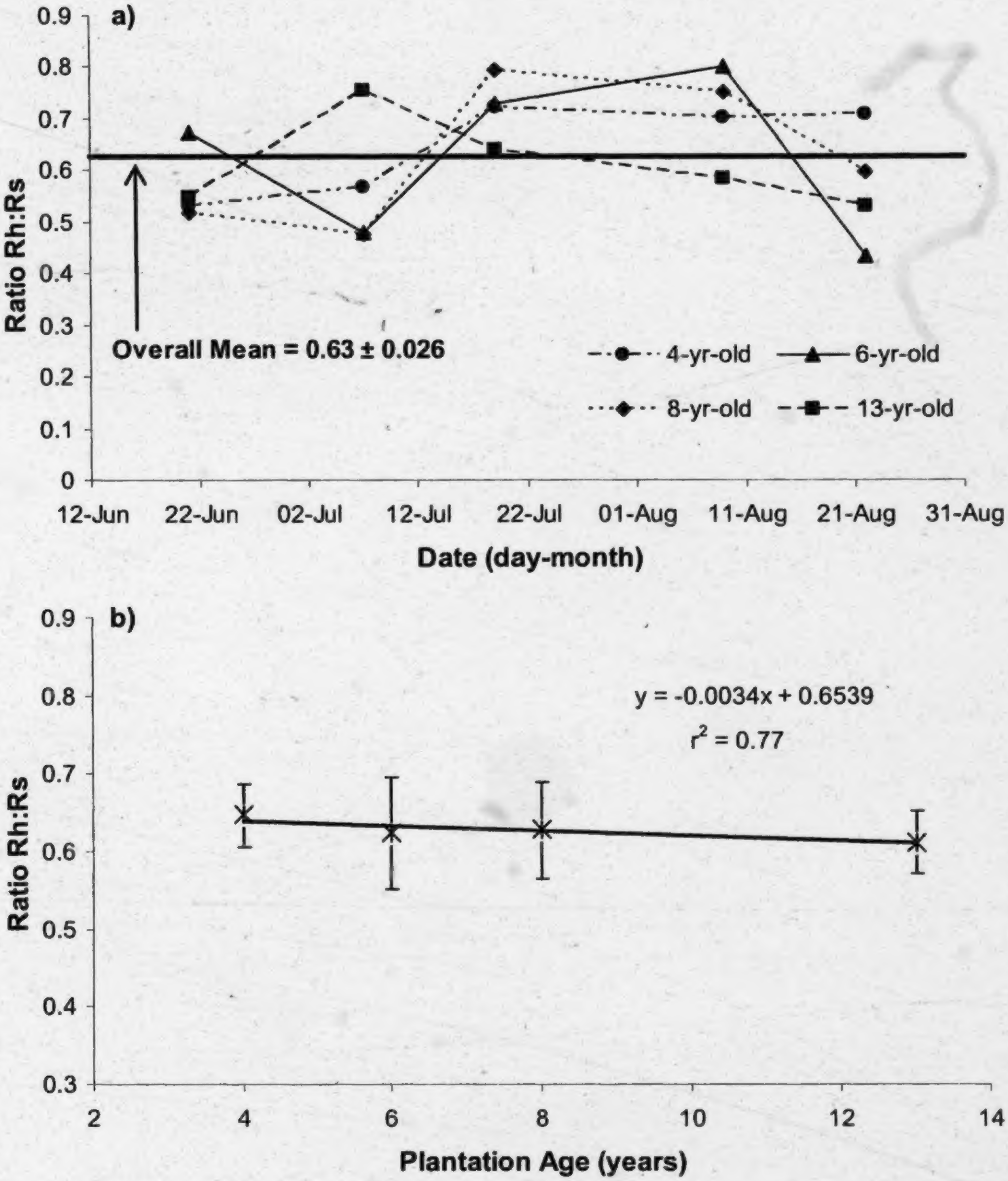


Figure 4.9. Contribution of heterotrophic respiration to total soil respiration in the 4 age-classes of the poplar plantation chronosequence across the five sampling dates (a) and relationship between mean contribution of R_h to R_s and plantation age in the chronosequence of plantations (b). Vertical bars in b) indicate ± 1SE. Note: 4- & 13-yr-old stands were Walker poplar, 6- & 8-yr-old stands were Northwest poplar.



5. GENERAL DISCUSSION AND CONCLUSIONS

5.1. General Discussion

The main objectives of this thesis research were to examine the immediate (short-term) response of an agricultural system (seeded to barley) to the establishment of a hybrid poplar plantation in terms of potential changes in CO_2 emissions and to determine the contribution of root respiration to total soil respiration in a chronosequence of hybrid poplar plantations in the boreal region of northern Alberta. Afforestation activities have the potential to sequester C from the atmosphere into the biosphere, primarily as wood biomass and soil C. Recent initiatives from government and industry to plant large areas of marginal agricultural land to hybrid poplar plantations are incentives to further develop our knowledge of C cycling in these types of systems to produce reliable estimates of GHG mitigations and C sequestration potentials. The following hypotheses were tested using two field experiments:

1) Soil respiration rates are higher in the barley as compared to newly established plantation due to lower fresh C inputs in the hybrid poplar plantation.
2) Dissolved soil organic C in the surface horizons is lower in the hybrid poplar plantations, again due to lower fresh C inputs.
3) Root respiration will increase with stand age as root biomass increases.
4) Root respiration will represent a higher proportion of total soil respiration as plantation age increases.

Hypothesis 1 was rejected as soil respiration rates were the same in both the barley and hybrid poplar plantation treatments. Soil temperature and volumetric water content, which are the main abiotic regulators of soil respiration, were also the same in both land-uses, hence supporting the findings that soil respiration rates were the same. Furthermore, previous land-use has been shown as an important factor in determining soil respiration rates as found by Grigal and Berguson (1998) who reported that soil C loss in the first year after land-use conversion was equal to that under previous land-use, consistent with the findings of this study. Although soil respiration rates were similar, dissolved soil organic C (DOC) concentrations in the soil were different between the two land-uses: Hypothesis 2 was supported by the results since lower DOC concentrations were found in the hybrid poplar plantation than in the barley plots, consistent with Post and Kwon (2000) who noted large losses of soil organic C due to the lack of fresh organic residue inputs in the early stages of forest growth. The results also suggest that the effects of soil DOC:DON ratio and microbial biomass on soil respiration counter-act each other. The higher DOC:DON ratio in the barley plots results in slower decomposition (Parmelee et al. 1989) of organic residues and suggests lower CO_2 efflux. On the other hand, microbial biomass was greater in the barley plots, which lead to greater rates of soil CO_2 efflux from a larger population of soil microorganisms, provided microbial activity and turnover rates were the same in both land-uses. These two factors balancing each other out may have resulted in the respiration rates remaining similar between the two land-use systems. In terms of C sequestration, I can conclude that the hybrid poplar plantations are a much larger source of C to the atmosphere than barley in the first year after land-use conversion at my research plots in northern Alberta. Respiration rates were the same; therefore the sink/source status of the site can be inferred from the net primary productivity (NPP) of the two land-uses. Since NPP is much greater in the barley land-use, the hybrid poplar plantation is a much greater source of C to the atmosphere in the first year after land conversion.

There was no significant increase in R_r with plantation age, therefore refuting Hypothesis 3. Although a weak relationship was found which indicates an increase in the contribution of R_r concurrent to an increase in plantation age, Hypothesis 4 was also refuted based on a lack of statistical significance of the aforementioned relationship. Only three studies have reported on stand age-related effects on soil respiration and components thereof (Subke et al. 2006). Both increases and decreases in the contribution of R_r as plantation age increases have been reported in the literature (Bond-Lamberty et al. 2004; Saiz et al. 2006). Other confounding factors that may mask the effect of plantation age on the components of soil respiration in the current study were too few replications in each age-class, a very small range of plantation ages, the possibly confounding effect of clone and the heterogeneity of soil in the research area (soil classification revealed that different soil Orders were present). The results (greater R_r during the early part of the growing season which coincides with a period of high root activity) do support the conclusion that R_r is tightly linked to tree physiological activity and phenology (root growth and construction), which has also been reported by others (Hanson et al. 1993; Lee et al. 2003).

A common problem with assessing the C sequestration potential of hybrid poplar plantations is the lack of background information (specifically C stock data prior to treatment application/plantation establishment) about the specific site being examined. Numerous studies have used paired-site comparisons (plantation soils compared to adjacent agricultural soils); however, historically, land-use may have differed between the two sites, resulting in inappropriate comparisons. This may lead to over- or underestimation of accrued C stocks in the soil. A thorough knowledge of C stocks at the time of land-use conversion would assure reasonable estimates of C sequestration within hybrid poplar plantations during plantation growth and at the end of the rotation. The land conversion experiment achieved this goal by characterizing soil C stocks in both the barley and hybrid poplar plantation plots the year prior to land-use conversion. I suggest this is an ideal foundation for future research which can allow for detailed monitoring and land-use comparisons over the entire plantation rotation, providing a reliable estimate of C sequestration in hybrid poplar plantations in the boreal region of northern Alberta.

Soils that are subjected to a new management regime, in this case land-use change from agricultural production to hybrid poplar plantation, will have a change in C inputs, resulting in a modification of C cycling processes. The changes in C inputs can be directly related to net ecosystem productivity (NEP) of a plantation; furthermore, the ability of a plantation to act as a source or a sink for C throughout multiple rotations will be directly reflected in soil C stocks. Guo and Gifford (2002) reported that soil C will eventually reach a new equilibrium once a new balance between C inputs and outputs is reached. As reported in numerous studies (Hansen 1993; Grigal and Berguson 1998;

Wang et al. 2006), plantations will be a source of C during the plantation establishment period. Subsequently, as the plantation ages, C will be sequestered in the form of biomass (above- and belowground) and soil C and become a sink for C when inputs exceed outputs; however the time required for this transition to occur in hybrid poplar plantations in unknown in the boreal region of Alberta with an anticipated rotation length of approximately 20 years. I propose that soil C stores will eventually be replenished to, or exceed, pre-cultivation C levels; nonetheless, the number of plantation rotations required to achieve these soil C levels remains unknown – as does the value of the pre-cultivation soil C level in most industrial-scale plantation operations. A hypothetical model of soil C accumulation coupled with NEP (source and sink phases of plantation cycle) which covers three plantation rotations, estimated at 22 years, is presented in Fig. 5.1. Soil C is increasing during periods where NEP is positive, indicating a C sink. Soil C is decreasing when NEP is negative, which is when C outputs exceed inputs, which occurs directly after a harvest disturbance during the plantation establishment phase. It is imperative to note that this model is simply shown to explain a concept and values of NPP, soil C and plantation age must be verified by future research. Moreover, detailed process-based models, for example *Ecosys*, a model being developed and tested at the University of Alberta (Dr. R. Grant), must be refined and tested to make quantitative estimates of soil C accumulation in hybrid poplar plantations such as the qualitative model presented in Figure 5.1.

A reduction in fresh C residue inputs to soil in the establishment phase of a plantation, resulting from land-use conversion from agricultural production, leads to a reduction in soil C, especially labile forms of soil C, which are the most readily available sources of C for microorganisms. This reduction in C inputs is a direct result of low net primary productivity (NPP) in the hybrid poplar plantations. The reduction of labile forms of C may actually be beneficial as microbial respiration should decrease as these forms of C are depleted from the soil. However, an important aspect also related to the decrease in organic residues is humification. Humified organic matter is a very recalcitrant form of C that can remain bound to soil particles for many years (retention time of 1000 years, Brady and Weil 1996). Without fresh C inputs, humification, and hence one form of C sequestration, will be reduced or eliminated completely from the C cycle. This can have a large impact on soil C processes: in one example, an input of 1475 kg C ha^{-1} into the humus C pool was reported in a corn field in a warm temperate region of the USA (Brady and Weil 1996). One solution that may mitigate the effects of low C inputs when establishing plantations is to let naturally occurring weeds grow in between the trees. Currently, the plantations are maintained by disking the space between the rows of trees to reduce competition for resources between young trees and fast-growing weeds. As a result, after the disking is complete, a ring of weeds remains tightly wrapped around the crop trees where the maintenance equipment cannot reach to avoid crop tree damage. Although the disking method of plantation maintenance is cost effective and a relatively fast procedure, other management options need to be developed and promoted. Maintenance of weeds in a small radius around the stem of crop tree and a cessation of disking in the space between tree rows may benefit both tree growth and C sequestration by allowing weeds to grow. It is however noted that new management strategies must also be time- and cost-effective to provide maximum benefits.

5.2. Suggestions for future research

Thus far, only three studies have examined the stand age-related effects on the contribution of root and heterotrophic respiration to total soil respiration (Bond-Lamberty et al. 2004; Czimczik et al. 2006; Saiz et al. 2006) and have reported contradictory results. In the current research, I found a weak trend which may indicate an increase in the contribution of R_r with increasing plantation age, consistent with Czimczik et al. (2006) and Bond-Lamberty et al. (2004, within the age range in our study). Numerous studies have reported differences in the Q_{10}, or sensitivity to temperature changes, of R_r and R_h (Boone et al. 1998; Hanson et al. 2000; Lavigne et al. 2003). Taking into account climate change, resulting from the greenhouse effect, and the importance of being able to predict changes in soil CO_2 efflux under future climatic conditions, more research into the partitioning of the sources of soil respiration in various ecosystem types is needed to better understand the dynamics of C cycling and response of R_r and R_h to environmental changes.

In the study of the contribution of heterotrophic and autotrophic respiration to total soil respiration, I used literature data and methods to estimate the contribution to soil CO_2 efflux originating from accelerated root decomposition from severed roots in the root excluded plots. Published reports have provided a wide range of decay rates (from 0.21 to 0.96 year^{-1}, see review by Subke et al. 2006) from various ecosystem types; this justifies the importance of making precise measurements of root decomposition in these types of experiments. Additionally, the dynamics of root decomposition over time must also be elucidated. Essential research questions that must be answered for the hybrid poplar plantations include:

1) How does the contribution of root decomposition to total soil CO_2 efflux change over time?
2) What are the relative decomposition rates of severed roots of different sizes (fine vs. coarse roots)?
3) At what point after root severing is the contribution of decomposing severed roots negligible?

These are merely a sample of questions which need to be addressed for the specific sites I studied and would provide more precise and reliable estimates of root decomposition and subsequent contribution to CO_2 efflux in the hybrid poplar plantations. The importance of answering such questions is reflected in Subke et al. (2006) who report that the decay rates are strongly dependant on local conditions.

Our results indicate a linear relationship between plantation age and the contribution of heterotrophic respiration to total soil respiration; however upon further analysis, it seems this relationship could be expressed otherwise. With a linear relationship, when the plantation age is zero (no trees), heterotrophic contribution to R_s is estimated at 65%; however theoretically, when no trees are present, R_h should be responsible for all the soil CO_2 efflux (provided no weeds are allowed to grow). Using best fit graphing software (Curve Expert 1.3, Daniel Hyams, Starkville, MS), and including an origin of 1,0 (R_h:R_s, plantation age), I was able to generate a model to predict the contribution of R_h to R_s according to plantation age ($r^2 = 0.999$, Fig. 5.2). The best fit logistic model indicates a rapid decline in the contribution of R_h to R_s from 100% at plantation age 0 to 79.9% in a 1-yr-old plantation, 67.1% in a 3-yr-old plantation and indicates stabilization at approximately 62% after 13 years. Complimentary work needs to be completed to elaborate on this type of relationship between the contribution of R_h to R_s. Continued sampling in the same plantations over the next decade would provide reliable values to verify the nature of the relationship in Fig. 5.2. In addition, only three studies have reported on stand age-related effects on the contributions of R_r and R_h, producing contradictory results. The ability to calculate approximate values for the relative contributions of R_r and R_h to R_s will improve our ability to estimate the effect of climate change on the C balance of hybrid poplar plantations as we already know from published reports that respiration from roots and microorganisms have different sensitivities to changes in soil temperature (for example see Boone et al. 1998).

I concluded from results in the land conversion trial that soil respiration rates were directly related to inputs from the previous year (2004), which is supported by work from Grigal and Berguson (1998). In future years, the pool of organic residues from the previous land-use will be depleted, and respiration rates will reflect this change in C dynamics. Therefore, more detailed work which seeks to assess the changes in various soil C pools, especially those which are readily accessible to microorganisms (such as DOC), would be valuable to facilitate the explanation of differences in soil respiration rates between the two land-uses during the plantation establishment phase. A valuable future project would be to evaluate the role of DOC in soil respiration in hybrid poplar plantations. The true effect of land-use conversion on soil respiration will not be evident until the soil responds to the new C input regime and reaches a new equilibrium (Guo and Gifford 2002). Monitoring of the soil C pools will reveal the changes in C cycling dynamics that occur prior to reaching this new equilibrium.

Carbon inputs to soil in both the barley and hybrid poplar land-uses is an important component of C cycling which was not examined in the current project. Litterfall provides fresh organic residues for soil microorganisms, which fuels heterotrophic respiration and was shown to be a large proportion of total soil respiration in the current study (58-72%). A comprehensive study which seeks to quantify C inputs in both land-uses is required to further understand the implications of land-use change from agricultural row-crops to hybrid poplar plantations on soil C stocks and respiration rates. Furthermore, this work would help support the conclusion that a lack of fresh residue inputs in the hybrid poplar plantation as compared to the barley sites may be an important factor in controlling soil respiration rates, especially once residues from the previous land-use are depleted in the hybrid poplar plantations.

In previous work completed in hybrid poplar plantations in the same research area as the current study, Saurette et al. (2006) reported preliminary results pertaining to the effect of spatial variability and rain events on soil respiration. The authors reported that soil respiration increased as the measurements were taken closer to the tree stems. For this reason, soil collars were consistently placed in the center of four trees to take soil respiration measurements to avoid any confounding effects of sampling location. This may have introduced bias and underestimated soil CO_2 efflux as soil respiration in the middle of four trees was found to be lower in the aforementioned study. Furthermore, Saurette et al. (2006) reported that soil respiration increased dramatically after a simulated rainfall event: increased soil respiration was greatest in the 20 minutes directly after watering; however respiration rates remained higher than pre-irrigation respiration values for up to two hours post-watering. Soil respiration sampling was not performed during or immediately after rainfall events in the current study to avoid over-estimation of respiration rates; however consideration of rain-driven increased respiration should be taken when annual C budgets are calculated. To elaborate on the comparison of respiration from trenched and un-trenched plots, similar simulated rainfall experiments would be valuable to assess the sensitivity of both heterotrophic and autotrophic respiration components to sudden increases in soil moisture content and availability.

In conclusion, the results from this work, in part, highlight the inherent variability of soils and site conditions in this boreal forest fringe. Early land-use conversion effects are masked by previous land-use, making the acquisition of verifiable soil C estimates a significant challenge. The difficulty in providing verifiable carbon sequestration estimates in soils at local levels (private and public sectors), and subsequent estimates of larger scale reporting (i.e. provincial) is likely to have repercussions in Canada's ability to report internationally as required by the Kyoto Protocol for the 2008-2012 commitment period. Efforts to sequester C in soils by implementing changes in agricultural practices and conversion of marginal agricultural land to hybrid poplar plantations must be supported by sound scientific results; however the intensity of measurement that would be required to provide accurate and repeatable values acceptable for international reporting may prove to be economically unrealistic for some participants in both the private and public sectors.

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Figure 5.1. Theoretical trend of soil C (%) increase and stabilization during three hybrid poplar plantation rotations coupled with theoretical net ecosystem productivity (NEP).

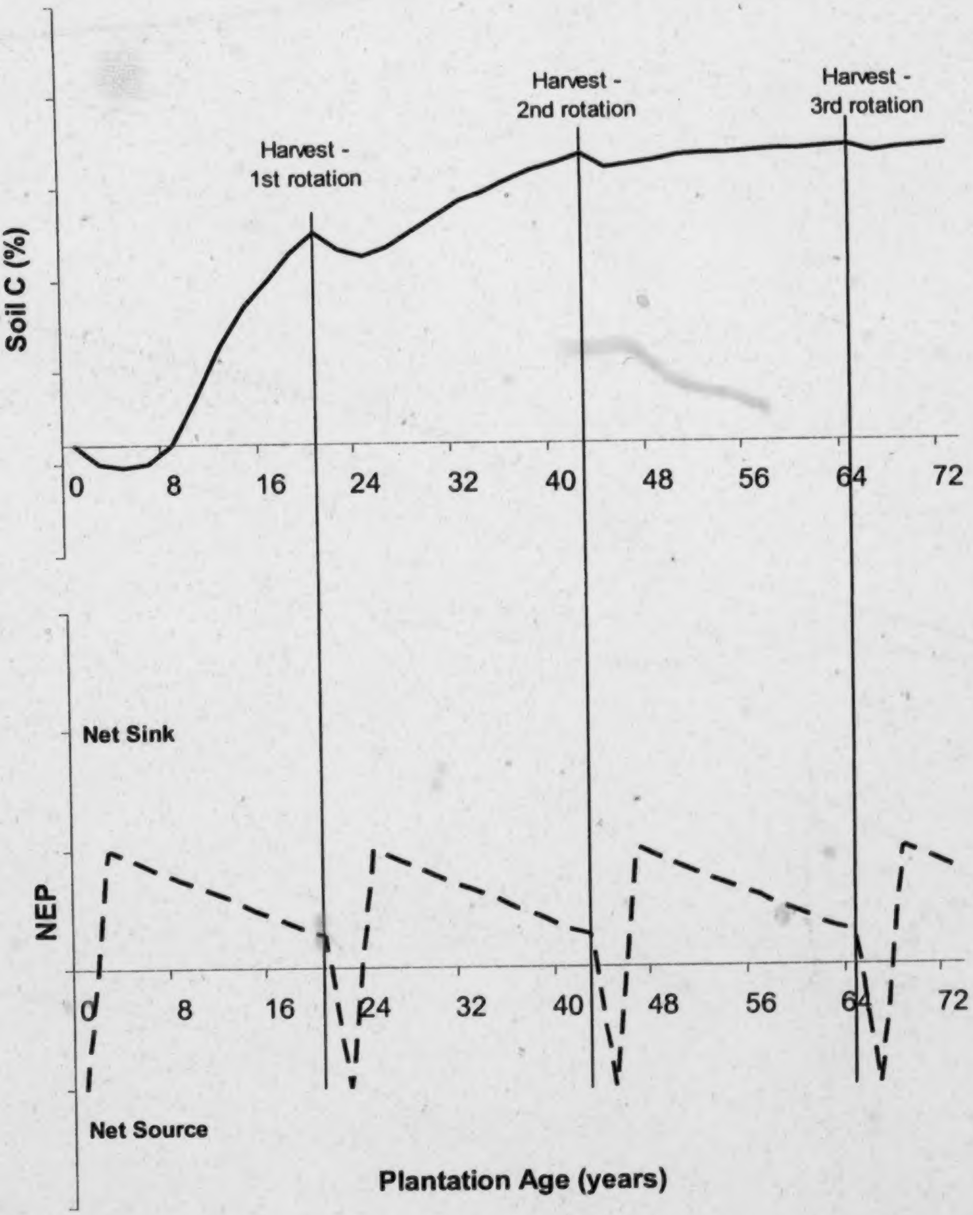
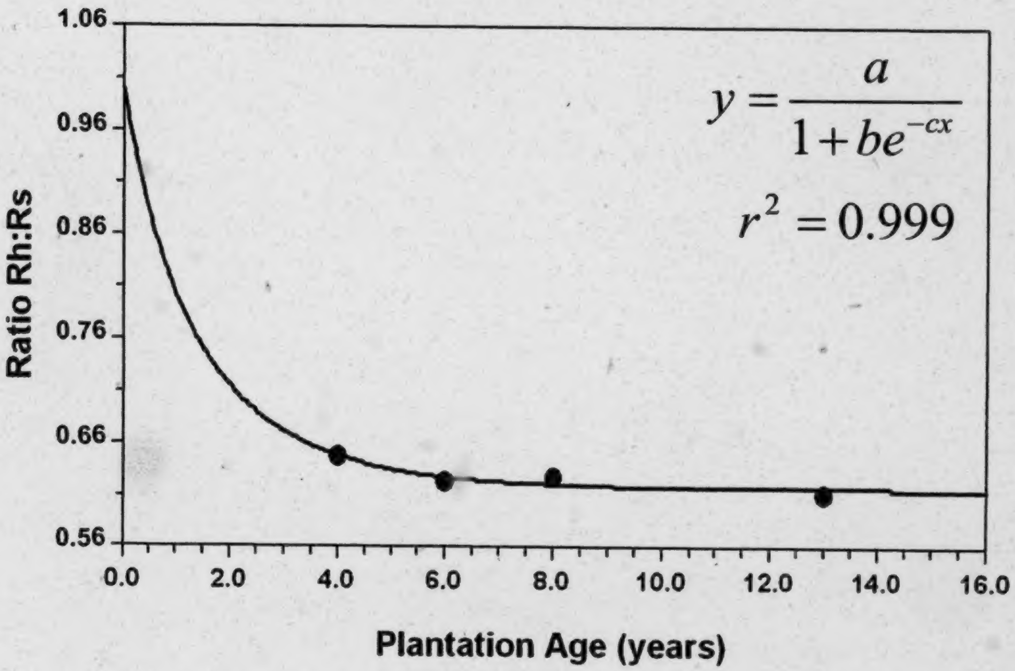


Figure 5.2. Best fit logistic model illustrating the relationship between the ratio of R_h to R_s and plantation age in the chronosequence of hybrid poplars.



APPENDIX I

Calculation of correction factors applied to trenched plot respiration values to estimate R_h.

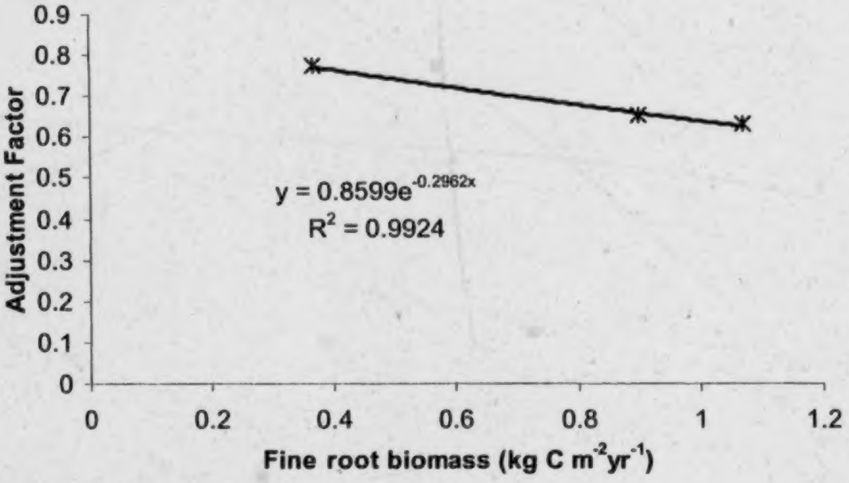
Table A1.1. Annual soil respiration (R_s), trenched-plot respiration (R_t), heterotrophic respiration (R_h) and root respiration (R_r) computed by Lavigne et al. (2003). The adjustment factor (AF) is computed using Equation 5 (annual R_h = AF * annual R_t) adapted from Lavigne et al. (2003).

Site	Year	Annual Rs	Annual Rt	Annual Rh	Annual Rr	Adjustment Factor	Mean Adjustment Factor
			(kg C m^{-2} yr^{-1})				
Cool	1998	0.73					
	1999	0.72	0.56	0.44	0.27	0.7857	0.7733
	2000	0.55	0.46	0.35	0.20	0.7609	
Midtransect	1998	1.23					
	1999	1.30	0.84	0.57	0.74	0.6786	0.6518
	2000	1.03	0.72	0.45	0.58	0.6250	
Warm	1998	1.54					
	1999	1.68	0.84	0.52	1.16	0.6190	0.6313
	2000	1.35	0.87	0.56	0.80	0.6437	

Table A1.2. Correction factors (cf) published by Lavigne et al. (2003) for cool, midtransect and warm sites. Fine root biomass (B_{fr}) was calculated using the correction factor equation (cf = 0.3 * B_{fr}) of Lavigne et al. (2003).

Site	Correction Factor* (kg C m^{-2} $year^{-1}$)	B_{fr}** (kg C m^{-2} $year^{-1}$)
Cool	0.11	0.367
Midtransect	0.27	0.9
Warm	0.32	1.07

Figure A1.1[3]**.** Relationship between mean adjustment factor (AF) and fine root biomass from Tables A1.1 and A1.2.



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[3] The equation generated from this relationship is used to calculate the AF value explaining fine root decomposition rates in the Al-Pac study plots.